Final Report February, 2009

Impact of Air Filtration on the Energy and Indoor Air Quality of Economizer-based Data Centers

in the PG&E Territory

Lawrence Berkeley National Laboratory

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Executive Summary

A significant portion of the energy in data centers is currently dedicated to provide cooling for the server equipment. Data centers must provide continuous air conditioning to address high internal heat loads (heat release from computer servers) and maintain indoor temperatures within recommended operating levels for computers. Air-side economizers, which bring in large amounts of outside air to cool internal loads when weather conditions are favorable, could save cooling energy. However, this technology is not widely adopted because the climate dependant energy savings from air-side economizers are expressed only qualitatively. Further, the lifecycle costing of this system is not well understood. A major barrier to economizer implementation is the fear of increasing pollutants levels in the data center during economizer cycle, and the fear that these pollutants could affect computer server reliability High efficiency HVAC filters are suggested as an option to effectively reduce particulate contamination inside the data center. Further, the energy implication of using improved filters in an air-side economizer system is also discussed. Strategies to reduce this economizer implementation barrier are explored in this study. Pollutants of concern are measured in a data center enabled with economizer operation while using air filtration of varying levels of efficiency.

Study results are summarized below:

1. The empirical energy data from the air-side economizer system (using MERV 7 filters) provided the maximum HVAC energy savings of 56% over a conventional data center without economizers. This translates to an overall data center energy savings of around 18% per annum. The improved filtration economizer scenarios also resulted in substantial HVAC savings of 38% in comparison to the conventional case.

2. The energy model of the Sunnyvale data center was run for 5 different PG&E climate zones. It indicated that the annual HVAC energy savings varied from 30% to 46% based on local temperature, humidity and dew point in the different zones. San Jose and San Francisco had similar HVAC savings of 33% due to humidity restrictions. This corresponds to an average DCiE of 0.72 which is substantially higher than the typical 0.55 value, which is as per the LBNL benchmarking studies.

3. An energy simulation of the impact of higher efficiency filters, like MERV 11 through 15, was carried out by incorporating a range of pressure drops. The HVAC energy

savings from these filter efficiencies varied between 31% and 37%. The higher end of the simulated HVAC savings were close to the measured value of 38% for the higher efficiency filters.

4. The lifecycle costing of the economizer (MERV 7) and conventional air handling unit based system provided a relative net present value of $0.3 M, with a simple payback period of 7 months for a 10-year life-cycle. The internal rate of return on investment was 170%.

5. The percentage of outdoor particles entering the data center when more efficient (MERV 14) filters are used is lower when the economizer is active compared that of conventionally used (MERV 7) filters when the economizer is off. This finding indicates that a data center with an economizer that uses MERV 14 filters can expect lower indoor particle concentrations than typically found in conventional data centers without economizers.

6. Measured outdoor particle concentrations are often highest during the times of day when economizers would be used, such as evening and night periods. This may be heavily influenced by the specific location of the data center.

7. A higher percentage of outdoor particles composed of black carbon or sulfate, both pollutants of concern, were measured in the data center compared to the general particle concentrations measured. A lower percentage of outdoor particles composed of nitrate, also a particle of concern, were measured in the data center compared to the general particle concentrations measured

The average particle concentrations measured at the data center under each filter scenario are shown in Table ES1. The Results section contains a discussion of the individual findings from each scenario.

Table ES1: Particle mass concentrations under each HVAC filtration scenario

			0.3-2.0 μm Particle Concentration (μg/m^3)			
Mesurement Period			High Air		Low Air	
Start Time	End Time	Filter Type	Out	In	Out	In
8/8/08 13:00	8/11/08 12:30	MERV 7	10.17	2.47	5.16	0.43
8/25/08 15:00	8/29/08 13:00	MERV 11	13.18	2.27	6.53	0.38
8/18/08 19:45	8/20/08 11:30	MERV 14	3.25	0.22	0.85	0.03

Objective

The goal of the project is to encourage the use of air economizers in data centers by developing a framework for making energy and lifecycle cost comparisons for various filtration options and to better understand the impact of climate on data centers. Specifically, this task aims to provide a real world understanding of the energy savings from using an air-side economizer. Further, this study works to overcome barriers to economizer use by addressing server failure concerns associated with air contaminants and by exploring improved filtration as a potential mitigation strategy. An energy model will be used that considers weather (temperature and humidity) and ambient particle concentrations for five different climate zones within the PG&E territory in California.

Data centers require continuous air conditioning to remove high internal heat loads (heat generated from IT and facility equipment) and maintain environmental conditions within IT equipment recommended operating levels. Air economizer cycles, which bring in large amounts of outside air to cool internal loads during mild outside weather conditions, could save cooling energy by reducing chiller operation. However, there is reluctance from many data center operators to use this common cooling technique due to fear of equipment damage from introducing outside air pollutants which over time could cause equipment failures. While improved filtration could be used to reduce indoor particle concentration this mitigation strategy appears to be rarely used. The performance of improved filtration has not been verified in data centers and high efficiency filters can increase flow resistance, which could potentially increase fan power.

In this study particle concentrations are measured in a data center enabled with economizer operation while using filtration of varying levels of efficiency. Particle concentrations are measured in terms of physical and chemical properties and documented under each filtration type for both active and inactive economizer use, while also monitoring any changes to operational energy use.

The results presented in this report have the potential to reduce the energy associated with data center operation by removing a common barrier to economizer implementation. This analysis of mechanical filtration in data centers identifies strategies that maintain contamination levels at or near non-economizer levels while maximizing energy savings and minimizing additional cost.

Methods and Procedures

Data Center Layout

The sampling site is the Net App data center in Sunnyvale, California. It is located within an office building. Energy and air quality information were gathered through the month of August, 2008. This Sunnyvale data center is designed with an economizer mechanical cooling system. In this system, conditioned air is ducted from air handling units (AHU) into the data center room to remove heat generated from the multiple rows of computer servers on the data center floor. The data center is served by eight separate AHUs. Each AHU has an air-side economizer, chilled water cooling coils, two supply and two exhaust fans. The cool conditioned air from the AHU is sent via a ducted supply to the ceiling vents in the data center. Cool air is drawn in by the fans in the server equipment. The warm air leaving the servers is then removed from the room through another set of ceiling vents and returned via a plenum to the AHUs, which are located in a mechanical room adjacent to the data center. At the AHU, some of the return air is exhausted while the rest is mixed with outside air, and passed through a row of filters, then conditioned and supplied to the data center again. Figure 1 shows the air-flow schematic of the data center and AHU rooms.

The system is fitted with an economizer, allowing the amount of outside air to adjust depending on outside temperature and humidity conditions. The facility manager operates the economizer within a temperature range. When the outside air temperature drops below the lower temperature setpoint, the amount of outside air entering the data center through the economizer increases to 100% (high outside air or economizer on mode). When the outside air temperature rises above the upper temperature setpoint, the amount of outside air entering the data center is reduced to approximately 1%, with return air from the data center accounting for the rest (low outside air or economizer off mode). This distribution of high and low outside air modes is consistent with common practice in data centers with economizers. The data center has no humidity control, but the economizer system locks out when the outdoor relative humidity is outside the 20%-80% range.

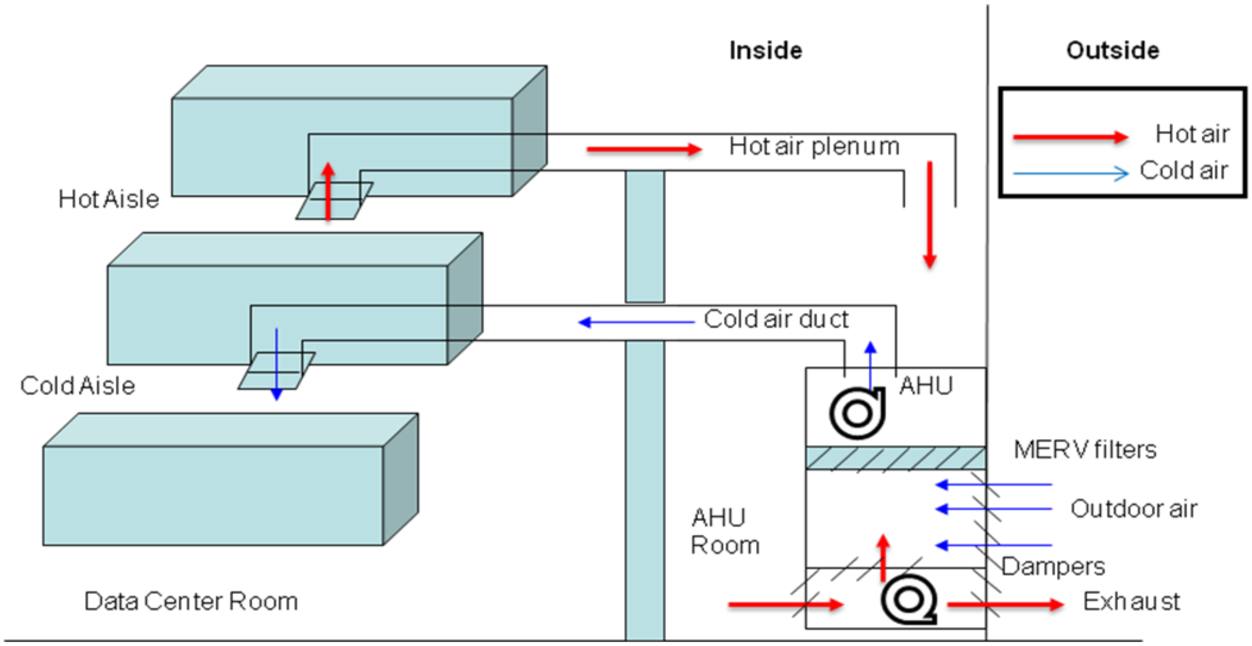


Figure 1: Airflow schematic of economizer system (chiller plant not shown here)

Experimental Design

Three different types of Heating Ventilation and Air Conditioning (HVAC) filters were installed during the monitoring period. Immediately before the monitoring period, new HVAC filters with a Minimum Efficiency Reporting Value (MERV) of seven were installed. These filters are commonly used at the Net App data center, consistent with most data centers. During the monitoring period the new MERV 7 filters were used for a week each in economizer on and off modes. The economizer on mode with MERV 7 filters is considered as the typical operation scenario, while the economizer off mode is the baseline operation similar to data centers that do not use economizers. At the end of the second week, the MERV 7 filters are removed and replaced with new MERV 11 filters. This is operated for a week, and then again replaced with MERV 14 filters. The increased MERV rating indicates a greater efficiency of particle removal by the filter. Hence, a week each of MERV 11 and 14 filters are considered the improved filtration scenario. The three ratings of MERV filters are shown in Figure 3.

Two particle counters were placed within the data center to measure absolute concentrations of both indoor and outdoor particle concentrations in the three different HVAC filtration scenarios. These real-time measurements allow the Indoor Proportion of Outdoor Particles (IPOP) to be calculated, which can be used to estimate filter performance and predict indoor particle levels for different outdoor concentrations. The indoor particle counter was located to measure the particle concentration entering the servers. The particle counter was placed on top of the server rack, with the intake tube extended in front of a server rack at a height of approximately 7 ft. This is shown in Figure 3. As shown in Figure 4, the outdoor particle counter was placed within the air handling unit at the outside air intake, prior to any filtration, to monitor the outdoor particle concentration entering the air handling units (AHUs) that serve the data center.

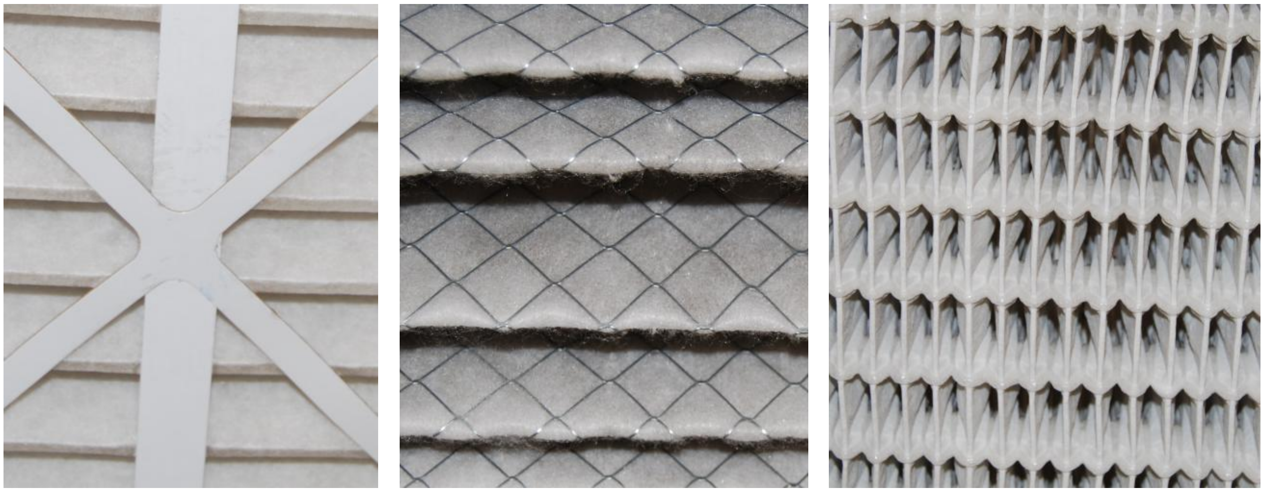


Figure 2: Close view of MERV 7, 11 and 14 filters from the experiment

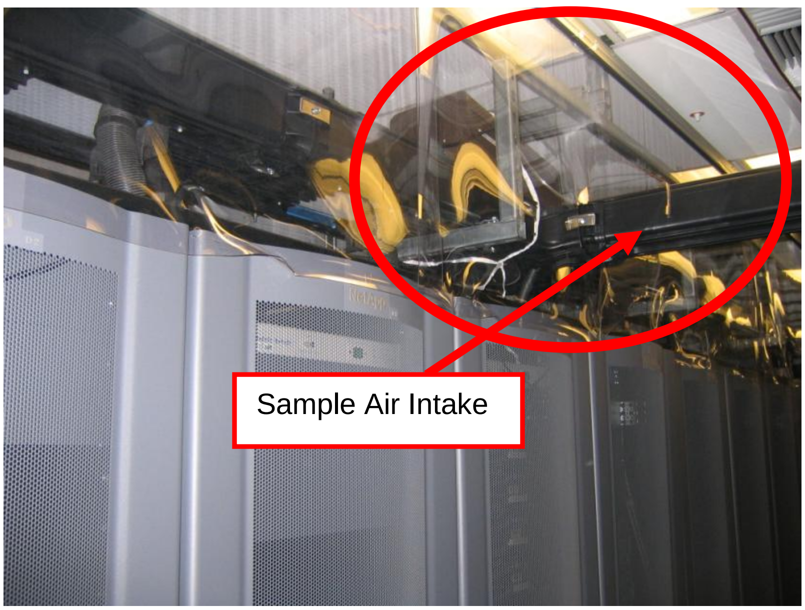


Figure 3: MetOne237B Optical Particle Counter above server rack

Figure 4: Second MetOne237B Optical Particle Counter located in AHU at the data center

Particles composed of black carbon were measured using a Magee Scientific AE22 Aethalometer placed within the data center. Black carbon particles, commonly referred to as “soot,” can be emitted during combustion processes and is commonly associated with tailpipe emissions from diesel trucks. An Aethalometer uses the light absorbing properties of black carbon to calculate particle mass by measuring differences in light transmission through a collected sample. The aethalometer system is shown in Figure 5. The Aethalometer used was programmed to calculate black carbon concentrations in one minute intervals. Two sets of 0.5 inch diameter copper tubing, each approximately 25 meters in length, were used to collect air from both inside and outside of the data center to the Aethalometer. A pump connected downstream of the tubing draws sample air through the tubing at 25 liters/minute. The air sample travels through the copper tube and enters a cyclone separator to remove particles larger than 2.5 μm in diameter. After passing through the cyclone, 4 liters/minute of the sample is then sent to the Aethalometer while discarding the remaining 19 liters/minute of sample air. Note that the 25 liters/minute flow rate is necessary for proper operation of the cyclone separator. A timed solenoid valve system was used to draw air through the outside air tubing for 20 minutes and then switch to drawing air through the inside air tubing for 20 minutes. The valves toggled in 20 minutes intervals throughout the experimental period.

Determining the composition of the particles entering the data center requires collecting particle mass samples and performing an Ion Chromatography (IC) analysis. Mass samples of airborne particle were collected by designing a particle capturing system. The particle capturing system consisted of a set of filters each for sampling outdoor and indoor air. The two filter systems along with the control valve setup are shown in Figure 6. The indoor setup was placed inside the data center, while the outdoor filter system was in the AHU room with a copper tube connecting it to sample outside air. This is shown in Figure 7. A detailed description of this system is presented in Appendix A.

Figure 5: Aethalometer system on the data center floor

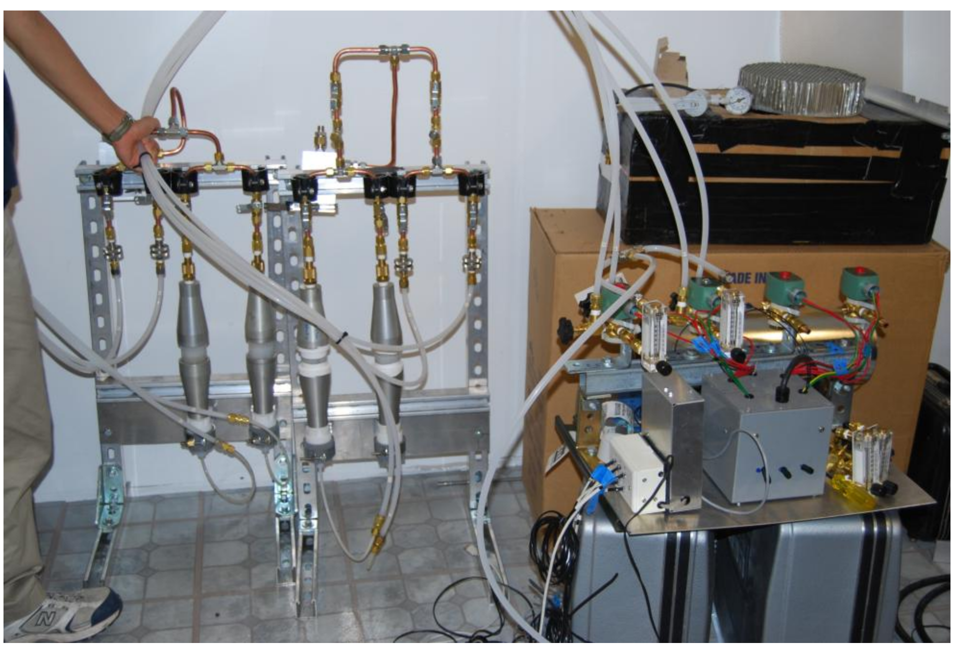


Figure 6: Indoor and an outdoor particle capturing filter systems along with the control setup

Figure 7: Particle Capturing System used for outdoor (left) and indoor (right) measurements

Measurement Protocols

Particle concentrations were measured using Met-One 237B optical particle counters (OPC). The particle counters were tested prior to the monitoring period to insure that each particle counter produced similar results under the same conditions. OPCs detect particles by correlating particle size to light scattering, so this measurement system is able to distinguish between particle size. However OPC measurement to do distinguish between particle composition, so the particles could be comprised of various materials, including carbonaceous (black carbon and organic carbon), ionic salts (sulfate and nitrate), or any other airborne material. The particle counters provide size-resolved counts for different size bins depending on particle diameter. Four size bins; 0.3-.5 µm, 0.5-.7 µm, 0.7-1.0 µm, and 1.0-2.0 µm, were used to represent fine particle mass concentration. The fine particle mass concentration was estimated by assuming a log-normal mass distribution of the particles across each measured size range. Assuming this type of mass distribution allows the mass median diameter within each bin to be calculated as the geometric mean of that bin. The particle density is assumed to be 1.5 g/cm^3. Equation 1 shows that the mass concentration is calculated by adding the mass from each size bin, i. The mass for each size bin is calculated as the product of the particle count (PC), particle density (ρ), and mass median volume, where the particle diameter, Di, is the geometric mean for the size bin.

Measurements were taken in 10 minute increments, where air is pulled through the particle counter at a rate of 0.1 ft^3/sec for three minutes. The counter then pauses for 7 minutes before beginning the next particle counting cycle.

Equation 1: Particle count to mass concentration conversion

$$MassConc = \sum PC_i \left(\rho \frac{\Pi}{6} D_i^{\,3} \right)$$

Aethalometer measurements of black carbon were taken in one-minute intervals, with the Aethalometer switching between analyzing outdoor and indoor air every 20 minutes. For each 20 minute period, the average of measurements between minute 9 and 19 were used to represent the black carbon concentration during that period. The first nine minutes of data were discarded because previous reports have shown that sudden changes in temperature and humidity that occur when the switching air sample locations, can corrupt the first few minutes of measurement while the Aethalometer equilibrates to the new condition. The final minute was discarded as a precautionary measure to ensure measurements within each 20 minute period were distinctly separated.

The air sample filters in the particle sampling system (Figures 6 and 7) were analyzed for particle content by a series of different procedures. Quartz filters were measured for concentrations of black carbon and organic carbon through Thermal Optical Analysis (TOA). This process involves exposing the quartz filters to increasingly higher temperatures and measuring the amount of carbon dioxide released. The molecular concentration of carbon dioxide released, and the temperature of that release is then used to back-calculate the amount of black and organic carbon particles that resided on the filter. The Teflon filters were equilibrated and then weighed with an off-site microbalance before and after the sampling experimentation to determine the absolute particle mass collected on each filter. The Teflon filters were equilibrated by placing them in a controlled humidity chamber for a minimum of 24 hours before each microbalance measurement. This was done to ensure that water molecules on the filter did not affect the measurements. The Teflon filters were then extracted to autosampler vials and analyzed for hygroscopic species, such as sulfate and nitrate, using a Dionex 2020 Ion Chromatograph. The nylon filters were analyzed for nitrate concentration using the same ion chromatography procedure. The cellulose filters were impregnated with citric acid to capture ammonia that was released from the dissociation of ammonium nitrate into ammonia and nitric acid. An ammonium electrode was used to correlate ammonia collected on the cellulose filter with electrical conductivity of solutions with known pH.

HVAC Energy Data Measurements

The energy measurements of the HVAC system was carried out at the Net App data center in Sunnyvale, California. The data center has an area of 6780 ft^2 with racks of servers arranged in cold-aisle hot-aisle configuration. The facility is cooled by air-side economizer (ASE) based air handling units (AHUs) that are located in a room adjacent to the data center. The ASE allows outside air to remove the heat generated by the servers when the outdoor conditions were within the operating set-points. Refer back to Figure 1 for an airflow schematic of the economizer system.

During the period of the study, for outside temperatures below 70^0 F the economizer system allows outside air to provide all the cooling. It operates in high outside air or economizer on mode. In this mode, all of the warmer return air from the data center is let outside through the exhaust dampers. When the outside air temperature rises above the setpoint of 70^0F, the amount of outside air entering the data center is reduced to approximately 1%, with return air from the data center accounting for the rest (low outside air or economizer off mode). During normal economizer operation, a partial economizer mode exists between the economizer on and off modes. The economizer operates in the partial mode when the outside air is higher than the temperature setpoint, but cooler than the exhaust air. In this mode the supply air is a mix of outside air and return air from the data center. In this study the partial mode is omitted to facilitate a clear cut-off between outside and inside air filter samples (during economizer on and off modes) from the particle capturing system. This would involve manual control of the economizer system. It was implemented in the study by observing the predicted change in outside air temperatures. It was approximately above 70^0F between 1 PM to 6 PM. In this interval the economizer was switched from outside air on (high air) mode to off (low air) mode. In the remaining 18 hours of the day the economizer operation was manually kept to full outside air mode. The energy implication of controlling the economizer system basically removed the hours of operation when the economizer would have run in partial mode. That means, the energy savings from using an economizer system would typically be more than measured in the study.

The ASHRAE standard for data center environments has an allowable range of 40-55% relative humidity, while the proposed range of 30-55% is being considered. The primary reason for the narrow humidity range is due to concern over electrostatic discharge (at very low humidity) and condensation of hygroscopic contaminants that can potentially cause electronic degradation. The Net App data center has no humidity control, but the economizer system locks out when the relative humidity of the outside air does not lie in the 20%-80% range. Measurements of outside and inside air temperature and humidity were recorded at different locations.

In the study, the HVAC energy savings from using air-side economizers is determined for three different HVAC filtration scenarios. The first scenario is the baseline case that consists of a chilled-water cooled AHU system with no economizer use. It is implemented at the data center by using new MERV 7 filters for a week while the economizer system is in off or low air mode. In the low air mode only 1% of the outside air is let inside the air delivery system. The second is the typical operation scenario for the data center using an AHU based economizer system with MERV 7 filters. The typical scenario is for a week during which time the economizer switches between on (high air) and off (low air) modes. The third scenario consists of two weeks of improved filtration with the use of 65% efficient MERV 11 filters, followed by 95% efficient MERV 14 filters. The MERV 11 filters are operated for a week, and then replaced by MERV 14 filters. The increased MERV rating indicates a greater efficiency of particle removal by the filter. Hence, a week each of MERV 11 and 14 filters make up the third improved filtration scenario. The pressure drop across the filters and in the common supply duct was measured for each filtration scenario. Pictures of the economizer-based AHU are shown in Figures 8 and 9.

Figure 8: Supply-side dampers (left image) and extended surface MERV filters of the economizer system

Figure 9: Supply (left image) and return air fans of the AHU

The authors would like to thank Dave Shroyer, Rick Turner, Rudy Tajalle, and Cameron Smith for their assistance and support during the study at the Net App data center.

Energy Modeling Protocol

Energy modeling is performed for the baseline and proposed HVAC design scenarios. The baseline scenario considers a data center using conventional chilled-water cooled AHUs. The AHUs are placed in a room adjacent to the data center room. Cool air from the AHUs passes through the ducted supply system and is discharged from the ceiling vents into the cold aisle. The server fans draw the cool air through the servers to remove the heat generated by the server equipment. The warm air rises in the hot aisle and travels back via the plenum to be discharged in the AHU room. The return air is re-circulated across the cooling coils, and discharged into the supply duct. Cooling is provided by a water cooled chiller plant.

The proposed design scenario incorporates air-side economizers in an AHU-based system. The air-flow configuration of this scenario is shown in Figure 10. In this scenario, outside air provides “free cooling” when the temperature is below the supply air dry-bulb temperature setpoint of the economizer system. This is the economizer on mode, and all the return air from the data center is sent out through the exhaust dampers and the re-circulating dampers are shut. The AHU uses exhaust fans in the return air-stream to remove the excess air through the exhaust dampers, thereby maintaining a slightly positive pressure in the data center room. When the outside temperature is higher than the supply air setpoint but below the return air dry-bulb setpoint, the economizer switches to partial mode allowing the chiller to provide some of the cooling. However, when the outside temperature rises above the return air setpoint, the supply-side dampers of the economizer close and full chiller operation is initiated.

The parameters of the baseline and proposed system were similar to the space and HVAC parameters of the Net App data center facility at Sunnyvale, CA. The area of the data center facility was 6780 ft^2 with an internal load density of approximately 131 W/sf^2. The supply air dry-bulb temperature was set at 68^0 F, and the return air was at 90^0F. The allowable relative humidity range was between 20%-80%. The proposed case uses an air-side economizer system, and hence the energy savings are climate-dependant. The energy simulation for the proposed scenario considered temperature and relative humidity variations for five different climate zones in the PG&E territory: San Jose, San Francisco, Redding, Sacramento, and Fresno. In addition, for the San Jose model different values of pressure drop for the supply-side of the economizer system were considered to understand the energy impact of higher efficiency filters. Details of the HVAC parameters, operating setpoints, and effect of climate and filter pressure drop on the energy savings are presented in Appendix C.

The authors would like to thanks Kim Traber and Hillary Price at Rumsey Engineers for running the models for the baseline and proposed cases.

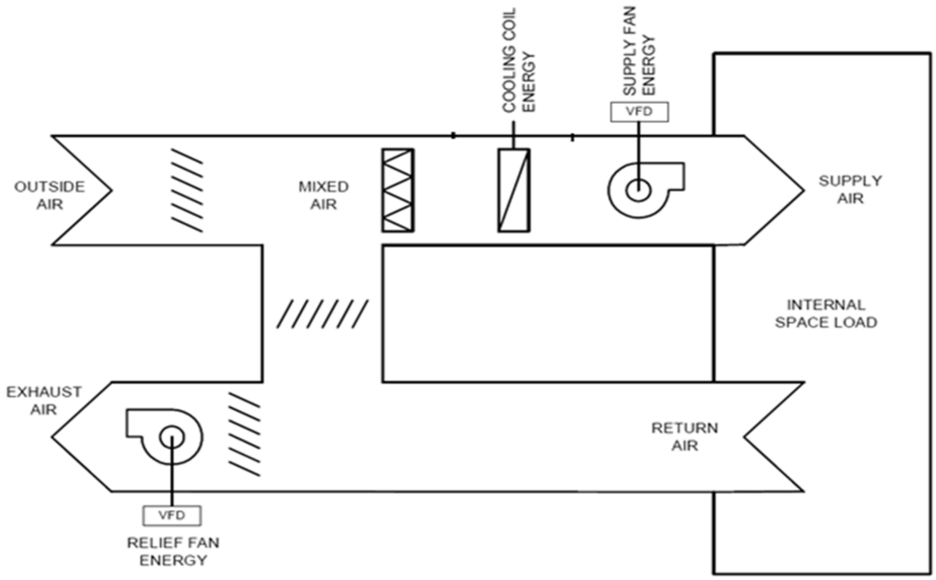


Figure 10: Air flow schematic for an air-side economizer system (courtesy Rumsey Engineers)

Life-cycle Costing of Air-side Economizer System

The lifecycle costing comparison between a baseline data center using AHUs, and an economizer based system (using MERV 7 filters) is determined using a model that simulates the energy consumption of the Net App data center at Sunnyvale. As mentioned in the previous section, the data center has an area of 6780 ft^2 with an internal load density of approximately 131 W/sf^2. The life-cycle costing assumes an 8% discount rate in the analysis. The inflation rate for electricity, material and energy costs is assumed to be 3%. Utility incentive is limited to 50% of the total incremental cost of implementation. Refer to Appendix C for details on the energy model and lifecycle costing.

Results and Discussion

HVAC Energy Data Measurements

Figure 11 shows the variation in HVAC measurements for the baseline, typical (MERV 7) and improved filtration (MERV 11 and 14) scenarios. For all the three scenarios, the upper part of the figure shows the variation in chiller and fan power consumption, and the lower part highlights normalized changes in outside dry-bulb temperature, relative humidity, and pressure drops in the supply duct and across the filter. The relative humidity, and pressure drops were normalized to a unit scale for the analysis, while for temperature alone, the rise rather than the absolute value is normalized. The rise in a particular day is the difference between the day's temperature and that of the coldest day during the observation period. Note that the measurements between days 7 through 10 of the study period were omitted from the final analysis because the operation of the economizer system was inconsistent. The total HVAC consumption was substantially greater in the baseline case in comparison to the typical and advanced filtrations scenarios. This is due to a decrease in chiller energy consumption from economizer use. However, as shown in the upper part of Figure 11, the fan power consumption in the typical and improved filtration scenarios increased only nominally with reference to the baseline. Comparison between the typical (MERV 7) and improved filtration (MERV 11 and 14) scenarios showed that with more efficient filters the chiller consumption increased while the fan energy changed nominally. This is contrary with expected behavior because with improved filters the pressure drop of the air supply system would increase, thereby increasing only the fan power consumption.

An analysis of the pressure drops downstream of the filters, and in the overall supply duct explains this anomaly. With improved filter efficiency, the pressure drop across the filters increased while the overall pressure drop of the supply duct decreased. The increase in pressure drop across the filters should have been compensated by increase in air flow rate of the supply fans. However, the supply air flow rate dropped because the supply fans were operating close to their maximum speed and were unable to provide the additional air flow. The decrease in air flow was compensated by increasing the chiller operation to lower the supply air temperature in the data center. Due to this additional cooling provided by the chiller plant, its power consumption increased during the improved filtration period. Further, the outdoor air temperature rose during the improved filtration period thereby increasing the cooling load on the chiller. Based on information from fan manufacturers and data center facilities, it was concluded that rarely do fans operate at or very close to their maximum allowable speed. The next section delves into modeling the HVAC system to estimate the energy savings if the supply fans could indeed vary their speed as a function of filter pressure drop.

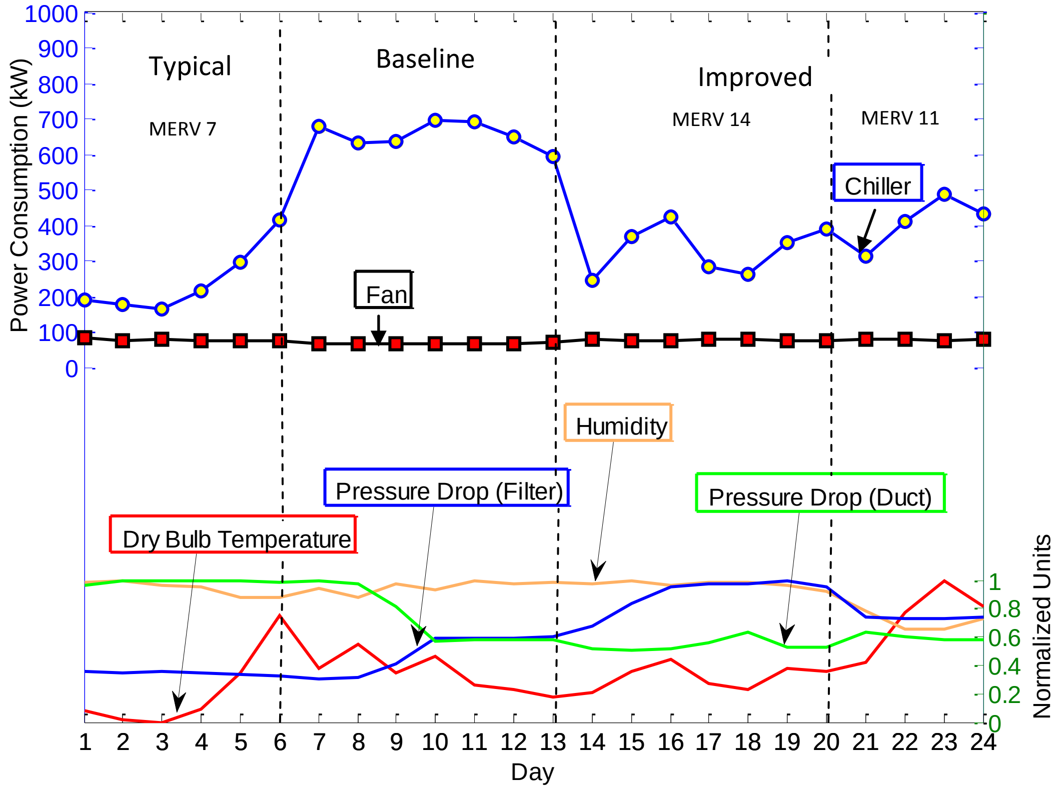


Figure 11: Chiller and fan power consumption (top part of graph) in comparison with normalized units of outdoor temperature, relative humidity and pressure drops across filter arrangement and supply duct

Figure 12 shows the breakdown of average HVAC power consumption into chiller and fan consumption for all the four scenarios. The savings numbers and percentages are presented in Table 1. In the typical scenario, the overall HVAC energy savings increased by 56% in comparison to the baseline. While in the improved filtration scenario, the HVAC savings increased by 38%. As per the LBNL data center benchmarking studies, HVAC energy consumption is about 33% of the total usage. Thus, the economizer based MERV 7 scenario provided about 16% overall data center energy savings in comparison to the baseline. It important to note that the energy savings from the improved filtration scenario would have been higher that 38% if the supply fans could provide the additional air flow instead of running the chiller. Further, the values of HVAC savings are based on measurements during a month (August) of the study and not averaged over a year. Also, energy savings from economizer use are climate dependant. The next section covers the variation in overall data center and HVAC energy savings as a function of climate.

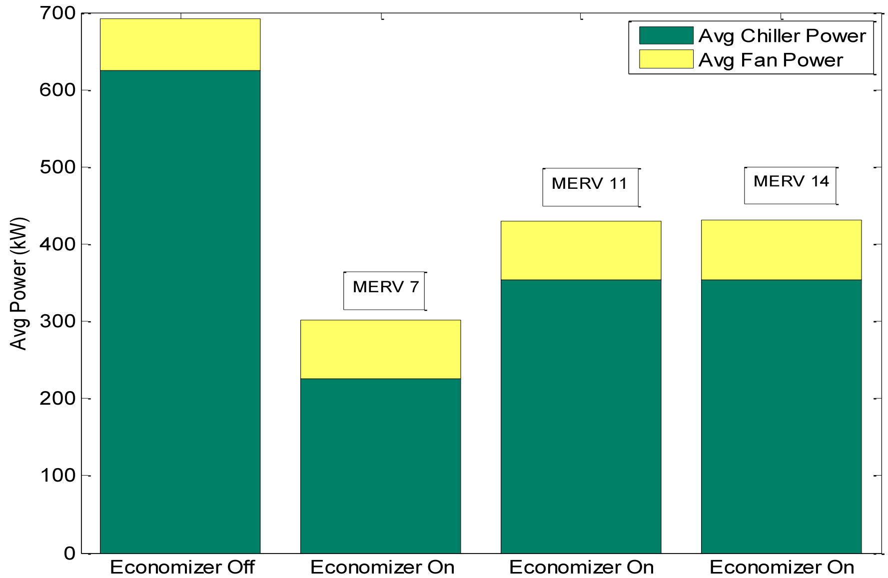


Figure 12: Average HVAC power consumption in the four scenarios

Scenario	Average chiller power (kW)	Average fan power (kW)	Total HVAC (kW)	Estimate of HVAC energy (GWh/y)	Savings with reference to baseline
Baseline (economizer off)	625	67	692	6.1	-
Typical (economizer on - MERV 7)	225	76	301	2.6	56%
Improved filtration (economizer on – MERV 11)	353	77	430	3.7	38%
Improved filtration (economizer on – MERV 14)	353	78	431	3.7	38%

Table 1: Average chiller, fan and total HVAC consumption during each of the four scenarios

Energy Modeling of Economizer-based Data Centers

The data center infrastructure efficiency (DCiE) metric is the ratio of the energy consumed by the server equipment to the total data center energy use. The higher the value of this metric, the better is the energy performance of the data center. According to LBNL benchmarking studies, the DCiE value for a typical data center is 0.55. A comparison of the DCiE ratios of the five climate dependant economizer based systems with the baseline case is shown in Figure 13. The performance of the baseline is better than a typical data center because it utilizes an efficient water-cooled chiller plant, and a low resistance supply duct system. Further, the transformer and uninterrupted power supply (UPS) systems are in a separate room adjacent to the data center, and hence do not add to the cooling load from the server equipment. The air-side economizer system for all five climate zones in the P&E territory performed significantly better than the baseline. Redding having the coolest climate had a DCiE of 0.73, while San Jose was 0.72.

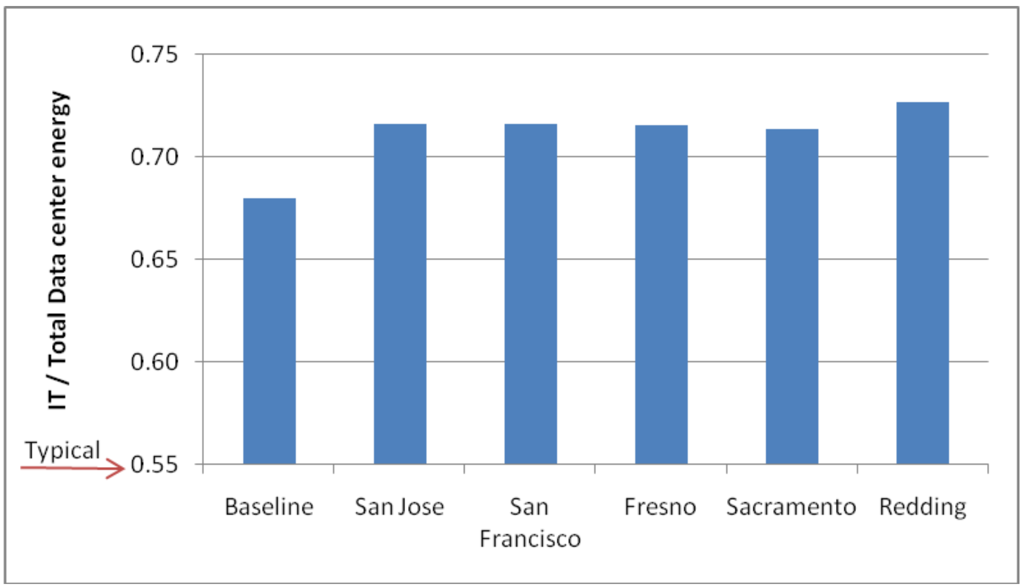


Figure 13: DCiE comparison of baseline and economizer based data centers

Figure 14 shows the disaggregation of the cooling systems' energy use for the baseline and air-side economizer scenarios for different climate zones. The energy loss due to waste heat from the transformers is also included since it is dependent on the HVAC energy consumption. The energy consumption of the data center server equipment, lighting and UPS systems is assumed to be constant for all the scenarios. The fan energy consumption in the economizer based scenarios does increase in comparison to the baseline, but the chiller energy savings far exceed this penalty. Table 2 shows the HVAC and overall energy savings of the economizer based system in comparison to the baseline scenario. In comparison to the baseline, the economizer system in San Jose would annually save 570 MWh which is equivalent to HVAC energy savings of 33%. Among the five climate zones, Sacramento was the warmest with HVAC savings of 30%, while

Redding being comparatively cooler garnered 46%. San Francisco had HVAC energy savings of 33% like San Jose and Fresno because of humidity restrictions (lockout outside 20-80% relative humidity) imposed on the air-side economizer. If humidity restrictions were removed the savings would improve substantially. The overall data center energy savings of the economizer based climate zones was 4.7-6.5% higher than the baseline. It should be noted here that the baseline data center considered in the model had a DCiE of 0.68 which is better than a typical value of 0.55.

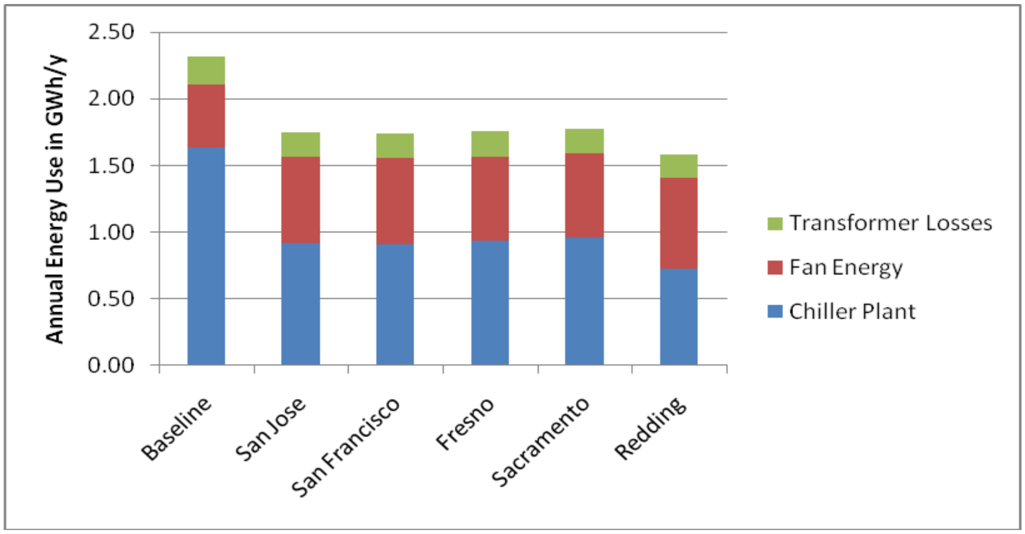


Figure 14: Climate dependent annual HVAC energy use of economizer-based data centers in comparison to the baseline

System	Baseline	San Jose	San Francisco	Fresno	Sacramento	Redding
HVAC energy in MWh/y	2,316	1,746	1,739	1,754	1,777	1,583
HVAC savings in MWh/y	-	570	576	562	538	732
HVAC savings %	-	32.6	33.2	32.1	30.3	46.3
Overall data center savings %	-	5.0	5.0	5.0	4.7	6.5
Annual energy cost savings in $	-	43,800	46,500	43,900	42,900	57,600

Table 2: HVAC energy and cost savings of baseline and air-side economizer scenarios

As described in the previous section on the HVAC energy data measurements, the energy savings from an air-side economizer system is dependent on the type of filters used in the air handling unit. Typically, most data centers use MERV 7 filters that remove more than 90% of particles in the size range of 3-10 µm. However, concern over particulate contamination from outside air has restricted the widespread use of air-side economizers. Improved efficiency filters reduce the entry of outdoor particulates in the data center, but as seen from the results in the previous section they may increase the overall HVAC energy consumption by changing the supply air flow rate. This happens in a situation when the fan system operates close to its maximum speed and is unable to maintain the flow rate with increase in filter pressure drop. This leads to an increase in chiller energy thereby decreasing the HVAC energy savings from an economizer based system. Table 3 provides a summary of different types of HVAC filters along with their typical pressure drops. The filter pressure drops are initial resistance values that correspond to a face velocity of 500 FPM.

Type of filter	Filter pressure drop or initial resistance (In. W.G.)
MERV 7 (pleated panel)	0.26-0.37”
MERV 11 (2” & 4” pleated panel)	0.3-0.5”
MERV 11 (1” pleated panel)	0.6”
Impingement type	0.5”
MERV 14 (4”) & MERV 15 (12”)	0.34-0.43”
Box & corrugated type	0.7”
High efficiency HEPA & ULPA	1.2”

Table 3: Different types of HVAC filters with their typical pressure drops

HVAC savings for San Jose in the previous analysis (refer Table 2) using MERV 7 filters only were 33%. Further analysis was conducted to quantify the effect of improved filtration on the fan and chiller energy consumption for the San Jose data center. The objective was to address the fan energy penalty of an improved filtration air-side economizer system on the overall savings. As shown in Figure 15, standard impingement type filters, extended surface filters (MERV 7, 11, 14 and 15), and clean room type high efficiency filters (HEPA and ULPA) were selected for the analysis. The HVAC energy savings from using MERV 11, 14 and 15 filters with pressure drops in the range of 0.3-0.6” W.G. was between 31-37%. Even if very high efficiency HEPA and ULPA filters were considered the HVAC savings were 21%. The recommended final resistance for most MERV filters was in the 1.5-1.7” W.G. range which corresponds to 16% savings. That means even with improved filtration the HVAC energy savings are substantial during the entire lifetime of the filter.

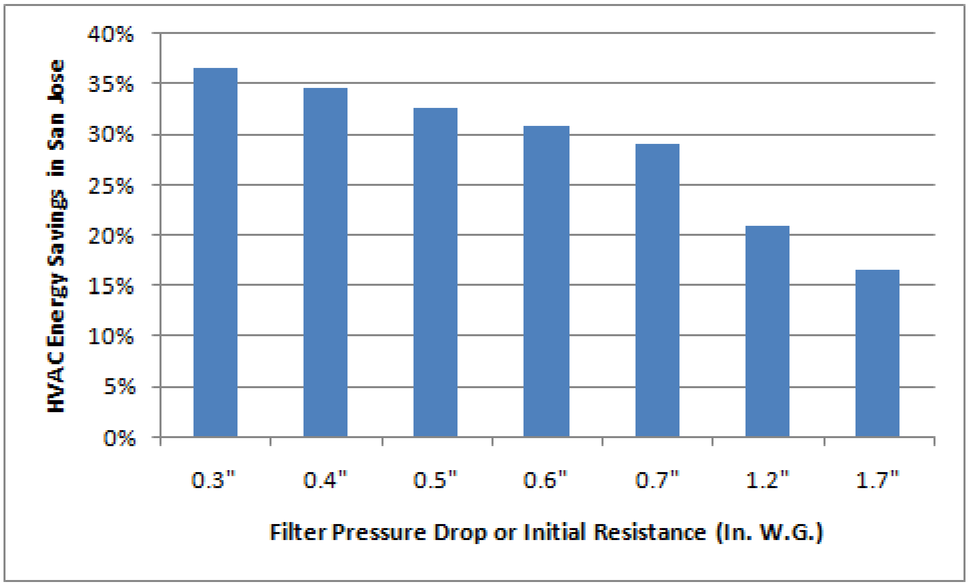


Figure 15: Variation in HVAC savings for different types of filters

Life-cycle Costing of Air-side Economizer System

Annual HVAC energy results of the air-side economizer and baseline systems are presented in Table 4. As discussed in the previous section, the baseline consists of an AHU chilled-water cooled system, while the economizer system utilizes air-side economizers in conjunction with AHUs. The HVAC energy savings of the economizer scenario is 32% in comparison to the baseline. The cost of implementing an air-handling system in both the scenarios is as per typical estimates for a data center in San Jose. The utility incentive is deducted from the difference in implementation cost to obtain the first cost. At the end of the first year of operation, labor and material costs are added to the first cost to generate the total expense. This expense figure is deducted from the energy cost savings to provide the net savings. A discount rate of 8%, and an inflation of 3% in energy, labor and maintenance costs are used in the life-cycle costing analysis.

	Baseline	Air-side economizer	Difference
First year energy cost	$1.15 M	$1.10 M	$43.8 K
Implementation cost	$0.25 M	$ 0.30 M	-$50.8 K

Table 4: Annual HVAC energy savings and implementation cost for baseline and air-side economizer scenarios in San Jose

The relative net present value is the difference between the net present values of the economizer and baseline data centers. A summary of the lifecycle costing of the economizer based system in comparison to the baseline for a 10-year period is presented in Table 5. Implementing an economizer based system has a simple payback period of around 7 months. The relative net present value increases from $0.3 M to $0.5 M for a 20-year period.

Simple payback	0.6 years
Relative net present value	$0.3 M
Internal rate of return	170%

Table 5: Lifecycle costing results of the economizer scenario with reference to the baseline

Particle Measurements

Particle counts measured at the Sunnyvale data center under different HVAC filter scenarios are represented as mass concentrations in Table 6. For each measurement period, both the indoor and outdoor mass concentrations are averaged separately for the hours under high air conditions (economizer on) and low air conditions (economizer off). The particle concentrations measured during the MERV 7 period match well with particle measurements conducted at this data center under a previous report (Data Center Economizer Contamination and Humidity Study, 2007). MERV 7 filters were also being used during those previous measurements.

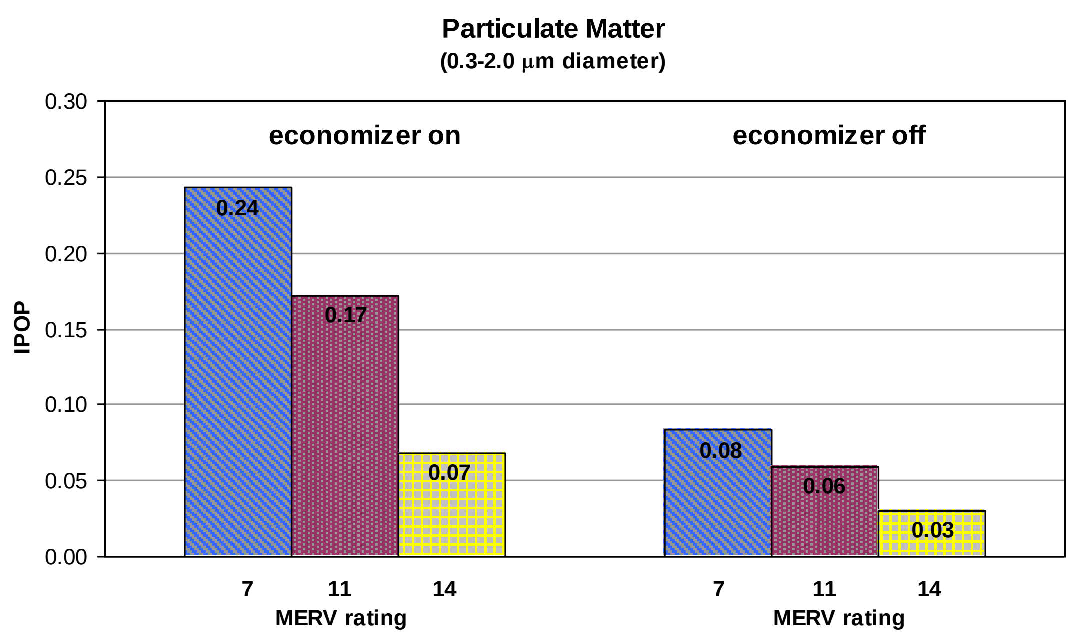
Table 6: Particle mass concentrations (OPC Measurements)

			0.3-2.0 μm Particle Concentration (μg/m^3)			
Mesurement Period			High Air		Low Air	
Start Time	End Time	Filter Type	Out	In	Out	In
8/8/08 13:00	8/11/08 12:30	MERV 7	10.17	2.47	5.16	0.43
8/25/08 15:00	8/29/08 13:00	MERV 11	13.18	2.27	6.53	0.38
8/18/08 19:45	8/20/08 11:30	MERV 14	3.25	0.22	0.85	0.03

The Indoor Proportion of Outdoor Particles (IPOP) is an indicator that can be used to compare the ability of the HVAC system to remove outdoor particles from entering the data center. IPOP values for high air (economizer on) and low air (economizer off) under the three HVAC filter scenarios measured are presented in Figure 16. As expected, the IPOP is relatively greater during high air periods and increased filter MERV ratings (increased removal efficiency) results in reduced IPOP values. A key finding shown in Figure 16 is that the IPOP value for the MERV 14 filters is lower when the economizer is active than the IPOP value of the conventionally used MERV 7 filters when the economizer is off. This finding indicates that a data center with an economizer that use MERV 14 filters can expect lower indoor particle concentrations than a conventional data center without an economizer and using MERV 7 filters.

As shown in Table 6, the IPOP value measured during the MERV 14 period is based on outdoor concentrations that are lower than the other two monitoring periods. The physical processes responsible for particle removal on filters are typically considered linear (i.e. the removal scales proportionally to the outdoor concentration). However, removal efficiency varies by particle size. Within the size range of the OPC measurements (0.3-2.0 μm diameter) the larger particles are more easily removed than the smaller ones. The lower outdoor particle concentration during the MERV 14 period is partly due to fewer large particles, which heavily contribute to overall mass, being airborne at that time. Evaluation of the OPC measurements show that smaller particles comprise a higher percentage of the total outdoor mass concentration during the MERV 14 period compared to the MERV 7 and 11 periods. This indicates that IPOP from the MERV 14 filters in this study represents a conservative measurement, and that lower IPOP values could be expected under higher outdoor concentrations. Furthermore, increased particle deposition on filters actually increases removal efficiency. This indicates that the IPOP measured here with new MERV 14 filters and exposed to low outdoor concentrations is, again, a conservative estimate since minimal particle deposition had occurred on the filters.

Figure 16: Indoor Proportion of Outdoor Particles (OPC Measurements)



Noticeable in Table 6 is that, within the same measurement period, the outdoor particle concentrations were higher when the economizer was operating compared to the hours when the economizer was shut off. This may be due to a combination of different factors. The economizers are active during nighttime hours; when the mixing height of the atmosphere can be lower, resulting in an increase in ambient particle concentrations. Also, the economizers are active during commute hours, increasing outdoor particle emissions from vehicular traffic. This data center can be particularly sensitive to vehicular emission since the air intake at the Sunnyvale data center is located less than 200 meters from a major freeway. The changes in outdoor and indoor particle concentrations with time are presented for each measurement period in Figures 17-19. The economizers were shut off approximately from the hours of noon to 6:00PM and a distinct decrease and then increase in indoor particle concentration can be observed corresponding with these times of the day. Fluctuations in outdoor concentrations are also clearly observed in Figures 17 and 18, though to a much less extent in Figure 19. The reduced outdoor fluctuations during the MERV 14 measurements (Figure 19) are probably due to the lower absolute concentrations during this period.

Figure 17: Indoor and outdoor mass concentrations with MERV 7 filters (OPC Measurements)

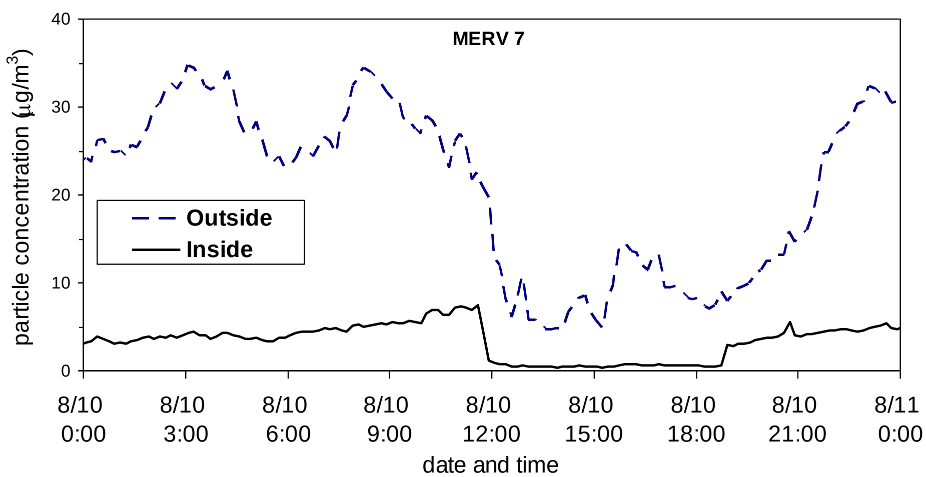


Figure 18: Indoor and outdoor mass concentrations with MERV 11 filters (OPC Measurements)

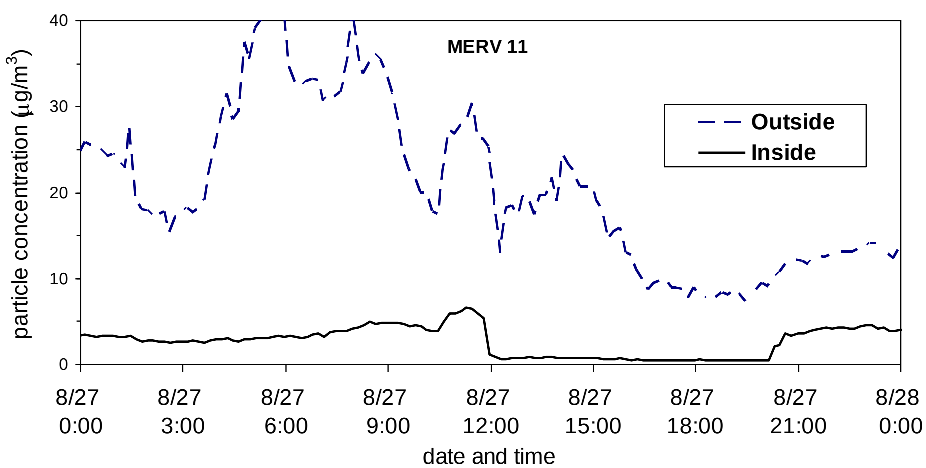


Figure 19: Indoor and outdoor mass concentrations with MERV 14 filters (OPC Measurements)

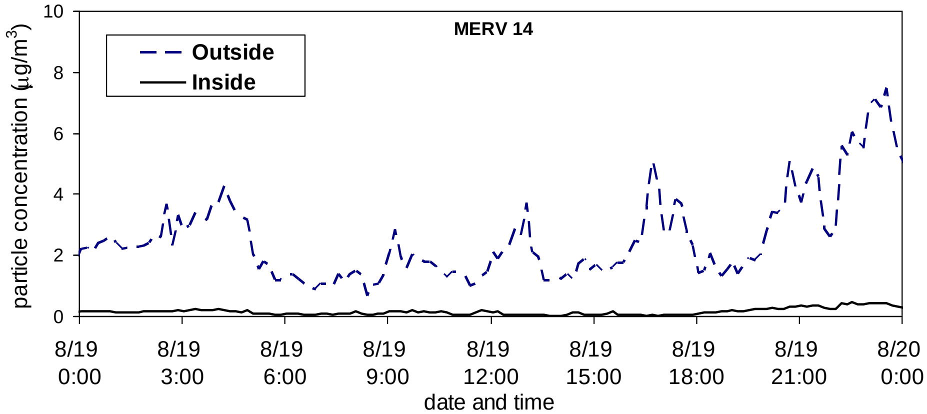
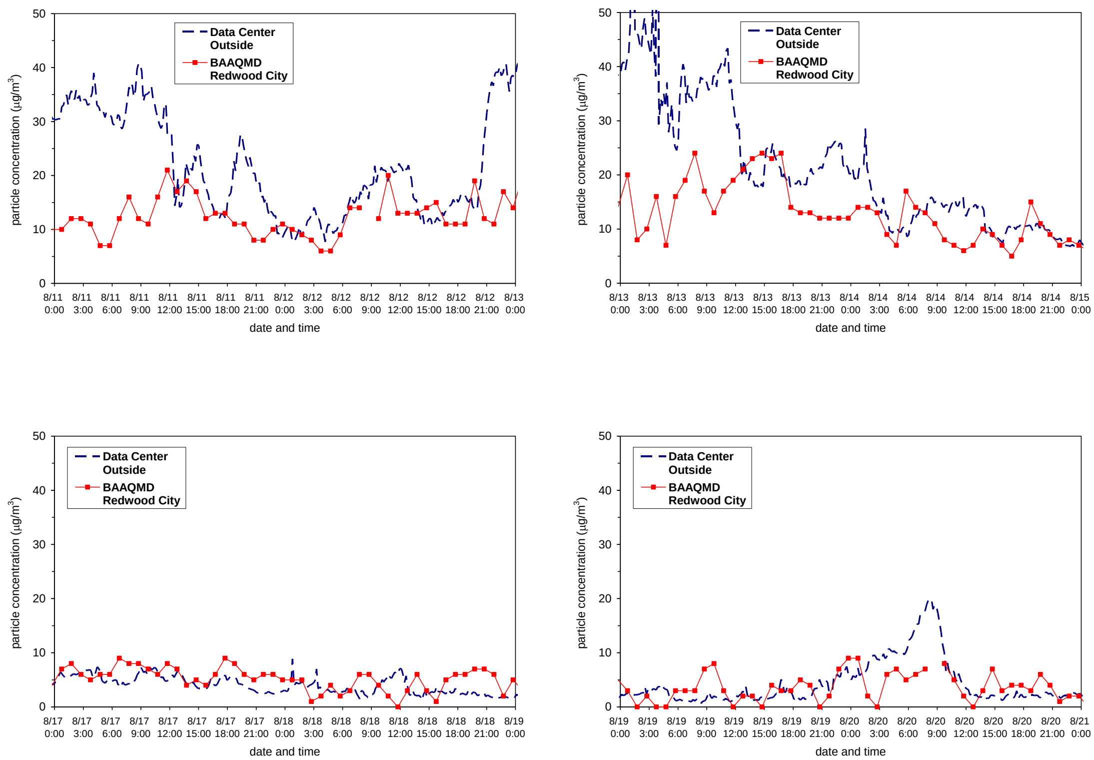


Figure 20: BAAQMD comparison of outdoor mass particle concentrations (OPC Measurements)



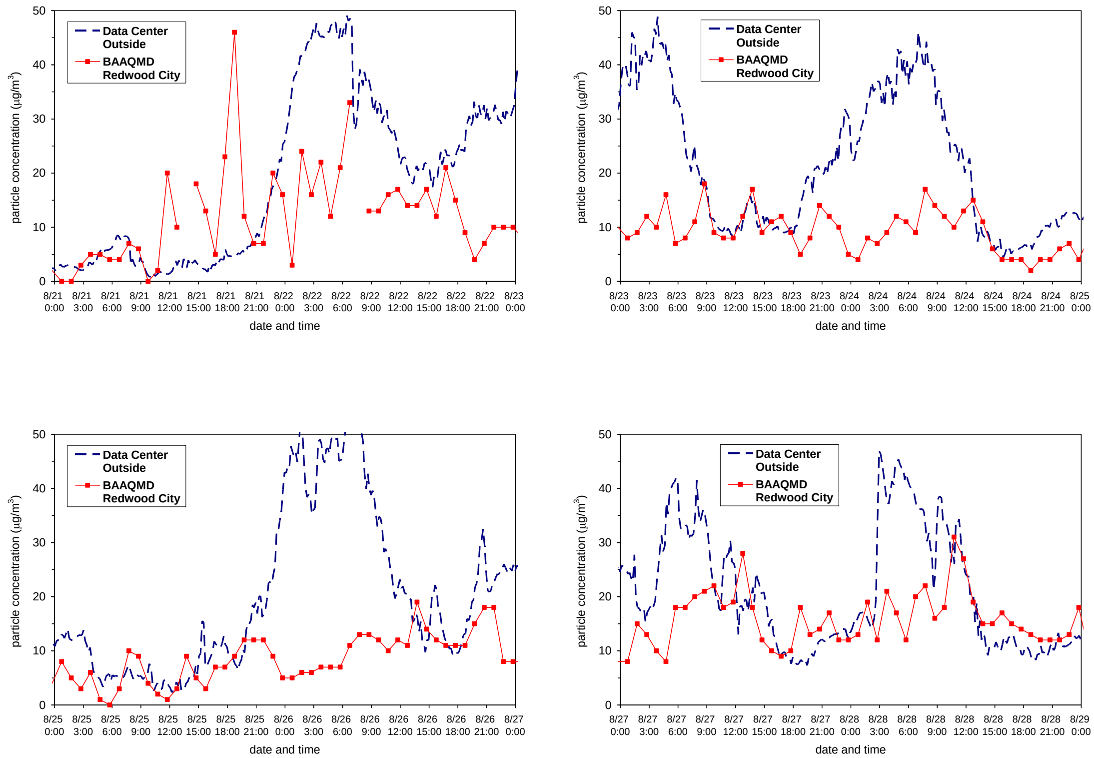


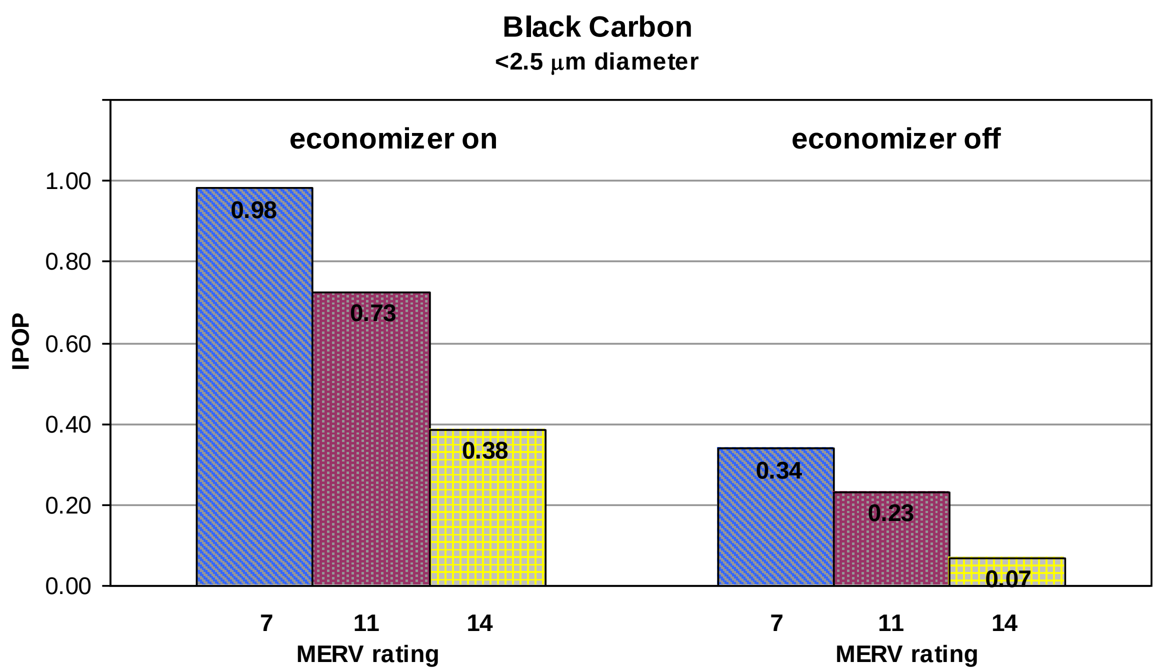
Table 6, as well as tables 7-9 presented below, all show drastically reduced outdoor concentrations of their respective particle types measured during MERV 14 filter monitoring period. To ensure that this outdoor concentration drop was not an indication of experimental error, the outdoor particle concentrations measured in this study were compared to regionally available outdoor particle concentration data from the Bay Area Air Quality Management District (BAAQMD) during these measurement periods. The BAAQMD data represents measurement from their sampling site in Redwood City, which is approximately 15 miles away from the Sunnyvale data center. Figure 20 shows a comparison of the outdoor concentrations measured in this study and the BAAQMD data. The relative drop in outdoor concentration during the MERV 14 measurements matches well for both data sets, indicating that the particle concentration drop is a result of meteorological changes rather than any changes in the study. Also observable in the BAAQMD comparison is that the somewhat rapid increases in outdoor particle concentration at the data center during many of the economizer on periods did not occur in the BAAQMD data. This highlights that particle emission sources in close proximity to the data center, such as the adjacent highway, may be significantly contributing to these increases in outdoor particle concentrations.

Table 7 shows the average black carbon measurements under each filtration scenario, again separated between economizer on periods and economizer off periods. The IPOP trends for black carbon is similar to that observed for particle, in that improved filtration reduces the black carbon IPOP and the MERV 14 IPOP during economizer on periods is comparable to the MERV 7 IPOP during economizer off periods. However, it is interesting to note that across all filter scenarios the proportion of black carbon that penetrates into the data center is greater than that of particle. For example, Table 7 and Figure 21 show that the MERV 7 filters essentially provide no protection from black carbon entering the data center during economizer on periods.

Table 7: Black carbon mass concentrations (Aethalometer Measurements)

			<2.5 µm Black Carbon Concentration (ng/m^3)			
Mesurement Period			High Air		Low	
Start Time	End Time	Filter Type	Out	In	Out	In
8/8/08 13:00	8/9/08 12:30	MERV 7	149.82	147.50	155.81	52.73
8/25/08 15:00	8/29/08 13:00	MERV 11	928.27	673.78	650.86	150.13
8/18/08 19:45	8/20/08 11:30	MERV 14	202.25	77.49	172.04	11.87

Figure 21: Black Carbon Indoor Proportion of Outdoor Particles (Aethalometer Measurements)

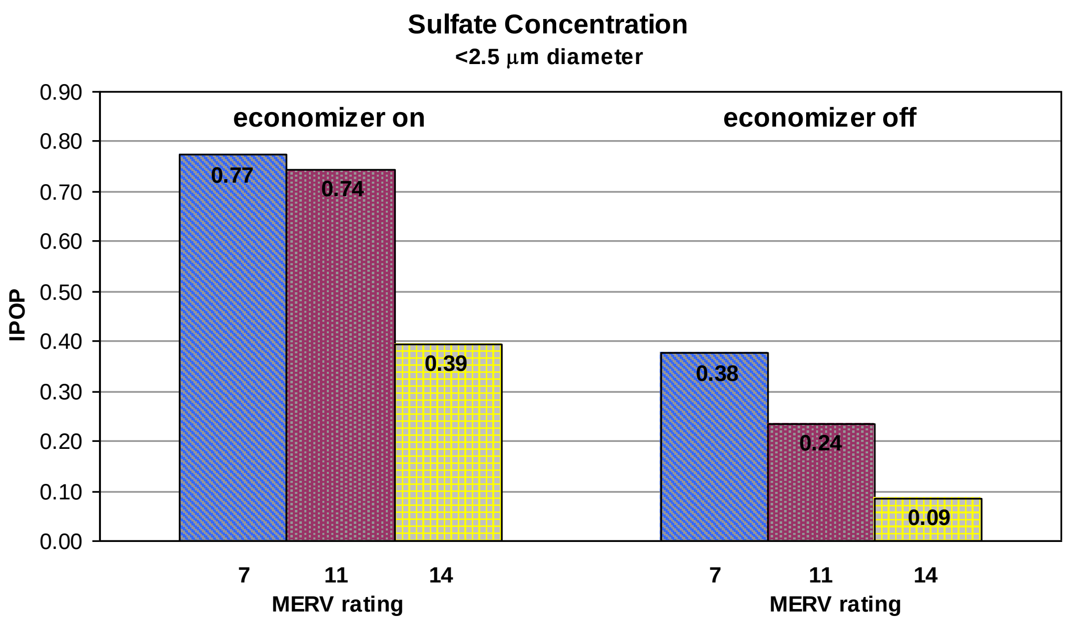


Indoor and outdoor concentrations of particles containing sulfate and nitrate particles are presented in Tables 8 and 9. As mentioned previously, particles containing these ions are of special concern in data centers due to their ability to absorbed water (deliquesce) can create conductive bridging between isolated conductors within computer servers. Figure 22 shows that sulfate particles tend to penetrate into the data center at a high proportion than the IPOPs measured from optical particle counting (the results shown in Figure 12). This indicates that, if sulfate is the primary particle type of concern, optical particle counting may not be an ideal proxy for estimating the proportion of dangerous pollutants entering a data center.

Table 8: Sulfate mass concentrations (Mass Based Measurements)

			<2.5 μm Sulfate Concentration (μg/m³)			
Mesurement Period			High Air		Low	
Start Time	End Time	Filter Type	Out	In	Out	In
8/8/08 13:00	8/11/08 12:30	MERV 7	1.84	1.42	1.48	0.56
8/25/08 15:00	8/29/08 13:00	MERV 11	1.24	0.92	1.58	0.37
8/18/08 19:45	8/20/08 11:30	MERV 14	0.94	0.37	0.35	0.03

Figure 22: Sulfate Indoor Proportion of Outdoor Particles (Mass Based Measurements)

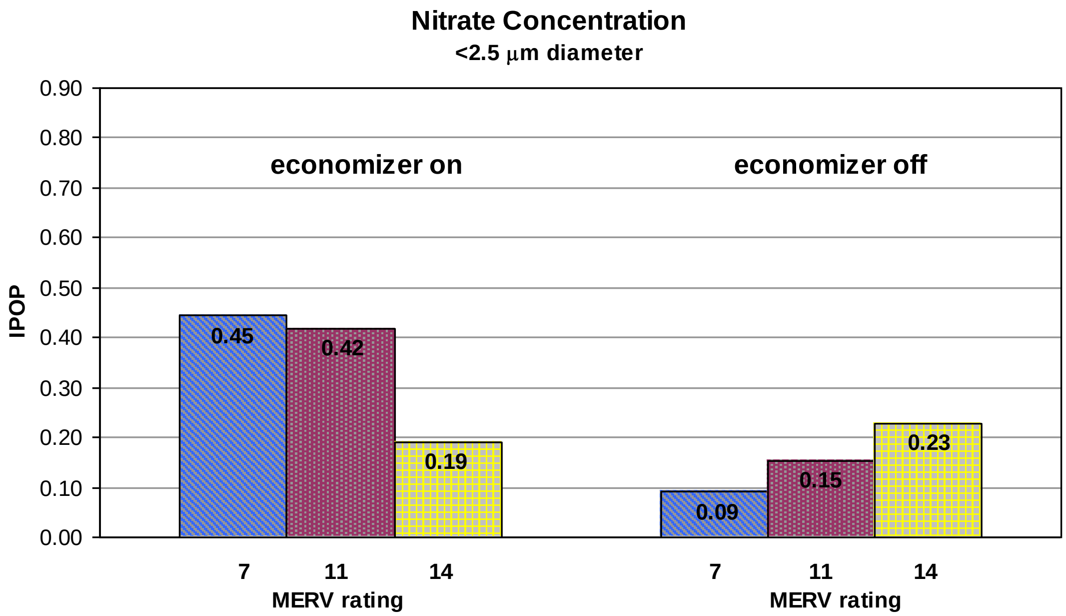


The IPOP measurements for nitrate particles, shown in Figure 23, are much lower than the IPOP counterpart for sulfate under nearly every scenario. The typically lower nitrate IPOP many to due to nitrate particles volatilizing once inside the data center. As mentioned previously, sulfate particles are thermodynamically stable while nitrate particles can easily convert to their gaseous constituents. The volatilization may also be responsible for the paradoxical nitrate IPOP values under the economizer off scenario, which could also be exacerbated by the very low nitrate concentrations measured during those periods.

Table 9: Nitrate mass concentrations (Mass Based Measurements)

			<2.5 μm Nitrate Concentration (μg/m³)			
Mesurement Period			High Air		Low	
Start Time	End Time	Filter Type	Out	In	Out	In
8/8/08 13:00	8/11/08 12:30	MERV 7	1.08	0.48	1.18	0.11
8/25/08 15:00	8/29/08 13:00	MERV 11	1.44	0.60	2.48	0.38
8/18/08 19:45	8/20/08 11:30	MERV 14	0.20	0.04	0.16	0.04

Figure 23: Nitrate Indoor Proportion of Outdoor Particles (Mass Based Measurements)



While results from this study show that MERV 14 filters allow economizer use while maintaining pollutant concentration at non-economizer levels, it is important to note that there is no indication that such low pollutant levels are necessary. Industry concentration limits vary considerably. ASHRAE's "Design Considerations for Data and Communications Equipment Centers" sets a limit that is acknowledged by ASHRAE as a conservative guideline. The ASHRAE particle concentration limits are shown in Table10. The ASHRAE guidelines suggest a fine particle concentration limit is set at 15 μg/m^3. The OPC measurements from this study primarily consisted of particles in the fine particle range and comparing our results to a 15 μg/m^3 annual limit shows the MERV 7 filters provide concentrations significantly below the limit. Measured sulfate and nitrate concentrations are also significantly below the ASHRAE limit. However, for data center operators that are not willing to tolerate any increase in pollutants levels, the use of MERV 14 filters appears to be a good alternative.

Table 10: ASHRAE annual average particle concentration limits for data centers

Contaminants	Concentration
Airborne Particles (TSP)	20 μg /m^3
Coarse Particles	< 10 μg /m^3
Fine Particles	15 μg /m^3
Water Soluble Salts	10 μg /m^3 max - total
Sulfate	10 μg /m^3
Nitrites	5 μg /m^3

Conclusion

Empirical results from a data center in Sunnyvale indicate that the HVAC energy savings in an economizer based system is around 56% in comparison to a conventional air-handling based system. An HVAC energy saving of 56% is equivalent to at least 18% overall energy savings in a data center. Also, it is important to note that the economizer benefits are climate dependent, and that the measurements were conducted in the summer month of August. Yearly measurements of the economizer system will provide overall energy saving estimates greater than 18%. The impact on energy savings from the use of higher efficiency MERV 11 and 14 filters was also measured for the air-side economizer system. The improved filtration scenario translated into 38% HVAC energy savings in comparison to the baseline AHU case. Apart from the energy savings, the improved filtration scenario also emphasized the need to minimize pressure drops, and maintain air flow rate in the supply side of the HVAC system. Further, energy simulation of the impact of higher efficiency filters, like MERV 11 through 15, incorporated a range of pressure drops. The HVAC energy savings from these filter efficiencies varied between 31% and 37%. The higher end of the simulated HVAC savings were close to the measured value of 38% for the higher efficiency filters.

The energy consumption of the Sunnyvale data center was simulated for 5 different PG&E climate zones. Climate dependent results of the economizer system indicate that the annual HVAC savings varied between 30% and 46%. San Jose and San Francisco garnered 33% HVAC energy savings in comparison to the baseline. This corresponds to an average DCiE of 0.72 which is substantially higher than the typical 0.55 value, which is as per the LBNL benchmarking studies. The energy savings would improve further if humidity restrictions were removed. The lifecycle costing of the economizer (MERV 7) and conventional air handling unit based system provided a relative net present value of $0.3 M for a 10-year period. The simple payback period was 7 months, with an internal rate of return on investment of 170%.

The potential for economizers to increase the particle concentration in data centers serves as a deterrent to economizer implementation, even if the increase is still be below the most conservative particle standards. The results of this study show that when MERV 14 filters are used during economizer use, the percentage of outdoor particles entering the data center is at or below the levels measured when using conventional MERV 7 filters without economizer operation. This finding indicates that a data center with an economizer that uses MERV 14 filters can expect lower indoor particle concentrations than typically found in conventional data centers without economizers. Measurement of chemical specific particles indicates that IPOP values for black carbon and sulfate are high than general particle concentrations measured, while the nitrate IPOP is lower. Results also indicate that measured outdoor particle concentrations are often highest during the times of day when economizers would typically be used, such as evening and night periods. Comparison with BAAQMD data indicates that this may be heavily influenced by the specific location of the data center.

Recommendations

Results from this project show that economizer operation can be achieved without increasing pollutant concentrations in the data center environment by implementing improved filtration. However, the results from this project also indicate, anecdotally, that improved filtration may reduce the energy savings associated with economizer use. Given these results, the need for enhanced filtration and a more thorough investigation of the energy penalty associated with these filters should be explored. Below is a description of future research tasks that would complement the research from this project.

1. Identify methods of failure and estimate failure probability:
   Work in collaboration with server manufacturers and the ASHRAE data center committee to document the types of failures that have occurred, such as current leakage or heat trapping. Identify the causes of the failure, beyond hygroscopic particles, and explain the believed mechanism by which these failures occur. Outdoor pollutant characteristics may vary by location within California. Review how the size and chemical composition influences equipment problems. Address the contribution of deposited fibers, which may enhance circuit failure rates by contributing to current bridging between isolated conductors. Identify and possibly developing potential methods to estimate the probability of failure under given pollutant conditions. For example, the applicability of percolation theory could be explored to correlate the probability of particle bridging with the volume of particles deposited in a given space.

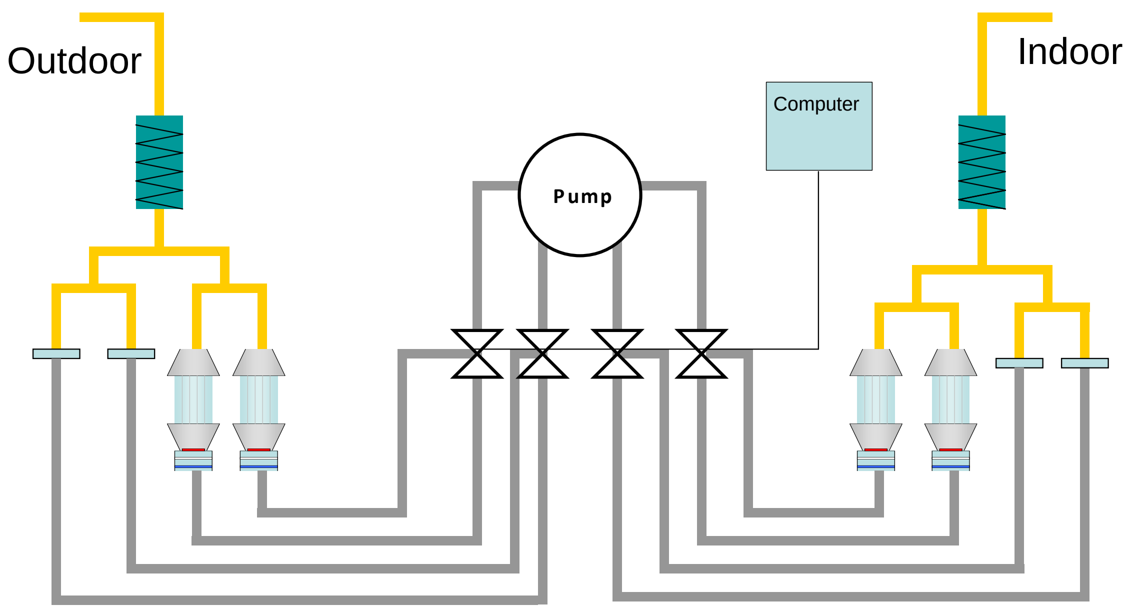
2. Determine energy penalty for enhance filtration in data center within the PG&E territory:
   The energy penalty of enhanced filtration observed at the Sunnyvale data center is specific to that HVAC design and the meteorological conditions during experimentation. Methods to prevent AHU fans from reaching maximum flow rates should be researched. Energy penalties should be estimated that allow results to be extrapolated to a broad range of data center designs. A combination of empirical practices and energy modeling could be performed to estimate the energy penalty of improved filtrations. Economic life cycle costing and environmental life cycle analysis of improved filtration could then be performed to determine when such filtration is warranted.

Appendix A

Particle Sampling System

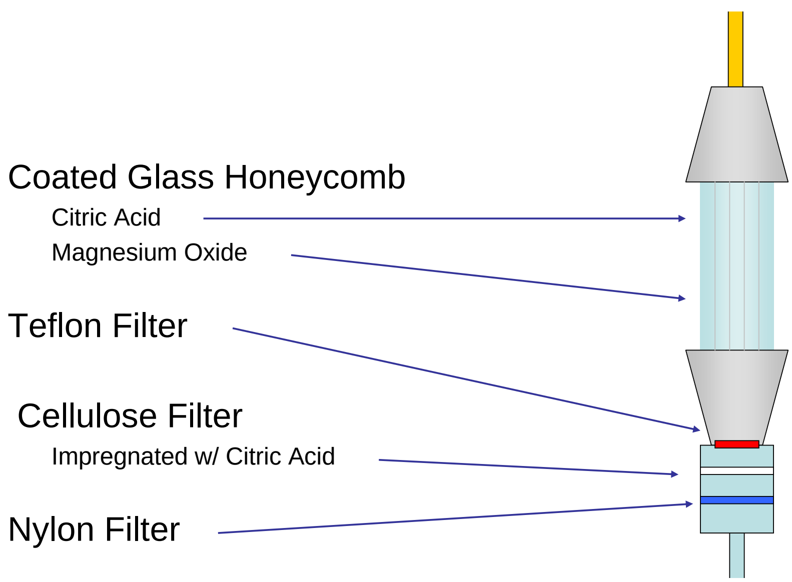
Two identical particle sample systems were developed; one to measure indoor air and the other for outdoor air. Each of these sample systems were connected through plastic tubing to a set of valves and then joined at a single pump used to draw air through the tubing. For each sampling system, sample air enters 0.5 inch copper tubing, approximately five feet in length, at a flow rate of 25 liters/minute. The air sample then enters a cyclone separator to remove particles larger than 2.5 µm in diameter. After passing through the cyclone, the copper tubing branches to allow sample air to pass through four sample filters; two quartz filters to collect elemental and organic carbon, and two "denuder" filters to determine ammonium sulfate and ammonium nitrate concentrations in the sample particle through IC analysis. The value system is designed to have sample air passes through one of the quartz filters and one of the denuder filters when the HVAC economizers are on, and the switch and have sample air pass through the other quartz and denuder filters when the economizer is off. As mentioned previously, the economizers were set to be off during the hours of noon to 6:00PM and on during the remaining hours. The valves in the sample systems diverted air to the appropriate sample filters according to this economizer schedule.

Figure 1: Schematic of particle sampling system



The denuder filter system was required so that the collected samples could be accurately measured for their chemical composition by IC analysis. Since IC determines the amount of specific ions, such as sulfate or nitrate, gases containing these ions must be removed from the air sample, so the ions measured can be accurately ascribed to particulate matter. The denuder system is shown in Figure 1. Sample air moves through the copper tubing from the top into a glass honeycomb structure, which separates the airflow into many narrow passageways. Gas molecules diffuse, or divert away from the airstream, much faster than particles. This causes the gas molecules to collide with the sides of the narrow passageways before exiting the honeycomb denuder. The particles, however, exit the honeycomb denuder before straying far enough to collide with the passageway walls. The honeycomb denuder was coated on one end with citric acid (an acid) and the other end with magnesium oxide (a base). The citric acid is use to react with and thereby remove any ammonia gas from the air sample. The magnesium oxide removes any nitrate and sulfate gases. After exiting the honeycomb denuder, the air sample is collected on a Teflon filter (marked in red in Figure 2). Ammonium nitrate particles are volatile and any ammonium nitrate particles collected on the Teflon filters can potentially volatilize into its constituent gases (ammonia and nitric acid). To account for the ammonium nitrate particles that may volatilize off the Teflon filters, two extra filters are added to the denuder filter system, downstream of the Teflon filter, to capture the gas phase constituents. A cellulose filter impregnated with citric acid (shown in white in Figure 2) is used to collect the volatilized ammonia gas. A nylon filter (shown in blue in Figure 2) is used to collect the volatilized nitric acid gas. Note that particle volatilization is not an issue with sulfate particles due to their thermodynamic stability.

Figure 12: Particle chemical speciation system ('denuder filter")



Appendix B

ACEEE 2008 Conference Publication

Energy Implications of Economizer Use in California Data Centers

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Abstract

In the US, data center operations currently account for about 61 billion kWh/y of electricity consumption, which is more than 1.5% of total demand. Data center energy consumption is rising rapidly, having doubled in the last five years. A substantial portion of data-center energy use is dedicated to removing the heat generated by the computer equipment. Data-center cooling load might be met with substantially reduced energy consumption with the use of air-side economizers. This energy saving measure, however, has been shown to expose servers to an order-of-magnitude increase in indoor particle concentrations with an unquantified increase in the risk of equipment failure. An alternative energy saving option is the use of water-side economizers, which do not affect the indoor particle concentration but require additional mechanical equipment and tend to be less beneficial in high humidity areas. Published research has only presented qualitative benefits of economizer use, providing industry with inadequate information on which to base their design decisions. Energy savings depend on local climate and the specific building-design characteristics. In this paper, based on building energy models, we report energy savings for air-side and water-side economizer use in data centers in several climate zones in California. Results show that in terms of energy savings, air-side economizers consistently outperform water-side economizers, though the performance difference varies by location. Model results also show that conventional humidity restrictions must by relaxed or removed to gain the energy benefits of air-side economizers.

Introduction

Data centers are computing facilities that house the electronic equipment used for data processing, networking and storage. Rapid growth in computational demand emerging from various sectors of the economy is causing strong rates of increase in servers and IT-related hardware (IDC 2007). Server performance has doubled every two years since 1999, leading to increasingly higher densities of heat dissipation within data centers (Belady 2007). A substantial proportion of energy consumption in data centers is dedicated to the cooling load associated with electronic power dissipation (Tschudi et al. 2003). A recent study estimates that US data centers account for 61 billion kWh or 1.5% of the nation's annual electricity consumption (US DOE

2007a). This corresponds to an electricity bill of approximately $4.5 billion in 2006 (EPA 2007). The environmental impact is substantial because 70% of the electricity in US is generated in power plants that burn fossil fuel (EIA 2007). Improved data center cooling technologies have the potential to provide significant energy savings. Cost savings and environmental benefits might also accrue.

A typical data center consists of rows of tall (2 m) cabinets or racks in which the servers, data storage and networking equipment are vertically arrayed. The cooling of data-center equipment is accomplished using computer room air conditioners (CRACs), which supply cold air to a raised-floor plenum beneath the racks. The CRAC system air handler is placed on the data center floor while chilled water in transported from compressor-based chillers to the CRAC cooling coils. More efficient cooling systems employ low outside air temperatures to reduce chiller load. Cooling towers that use ambient air to directly cool or precool the chilled water are known as water-side or fluid-side economizers. This type of system has been claimed to cut cooling-energy costs by as much as 70% (ASHRAE HVAC Fundamentals Handbook 2005) during economizer operation. Based on local weather data in San Jose, water-side economizers can be used for more than one-third of the year (PG&E 2006). An alternate data center arrangement uses air-handling units (AHU) and an air-side economizer. Such systems directly provide outdoor air for cooling whenever the temperature of outside air is lower than the set-point for return-air temperature in the data center. In San Francisco's cool climate, outside air could contribute to some level of air-side cooling for nearly all hours of the year (Syska Hennessy 2007). The use of air-side economizers brings with it an associated concern about contamination including moisture from humidity that may possibly threaten equipment reliability. Deliquescent sulfate, nitrate and chloride salts, in a humid environment (> 40% relative humidity) can cause corrosion, accumulate and become conductive, and may lead to electrical short-circuiting (Rice et al. 1981; Sinclair et al. 1990; Litvak et al. 2000). In this paper, the energy implications of a data center using a CRAC system will be compared with alternative cooling systems using air-side or water-side economizers for five different California climate zones. The modeling results and discussion focus on understanding the energy implications for both type of economizers and their effectiveness in different climate zones. The equipment reliability concerns associated with air-side economizers are acknowledged to be important, but addressing it is beyond the scope of the present paper.

Methods

Data center design scenarios

Energy-use simulations were performed for three different data center HVAC design scenarios (Figure 1). The baseline case considers a data center using conventional "computer room air conditioning" (CRAC) units. In this scenario, CRAC units are placed directly on the computer room floor. Air enters the top of a CRAC unit, passes across the cooling coils, and is then discharged to the underfloor plenum. Perforations in the floor tiles in front of the server racks allow the cool air to exit from the plenum into the data-center room. Fans within the computer servers draw the conditioned air upward and through the servers to remove equipment-generated heat. After exiting the backside of the server housing, the warm air rises and is transported to the intake of a CRAC unit. Most air circulation in the baseline scenario is internal to the data center. A small amount of air is supplied through a rooftop AHU to positively pressurize the room and to supply outside air for occupants. Cooling is provided by a water-cooled chiller plant. Refrigerant in the chillers is used to cool water through heat exchangers at the evaporator. The chilled water is then piped to the CRAC units on the data center floor. Waste heat from the chiller refrigerant is removed by water through heat exchangers in the condenser. Condenser water is piped from the cooling towers, which cools the water through interaction with the outside air. This baseline design is common to most mid- to large-size data centers (Tschudi et al. 2003; Rumsey 2005; Syska Hennessy 2007).

The water-side economizer (WSE) scenario assumes a CRAC unit layout similar to that of the baseline case, except that additional heat exchangers are installed between the condenser water in the cooling towers and the chilled water supplied to the CRAC units. Under appropriate weather conditions, the cooling towers can cool the condenser water enough to cool the chilled water in the CRAC units directly, without operating the chiller plant. The CRAC units and chiller plant are assumed to be the same as in the baseline scenario.

The air-side economizer scenario (ASE) requires a different type of air delivery than typically found in a data center with conventional CRAC units. AHUs are placed outside of the data center room, commonly on the rooftop, and air is then sent to and from the computer racks through ducts. A ducted air delivery system creates greater air resistance than a conventional CRAC unit layout, though this system better prevents cold and warm air from unintentionally mixing within the data center. When the outside air temperature is equal to or below the temperature of the air supplied to cool the server, the AHU can directly draw outside air into the data center and exhaust all of the return air after it has passed across the computer servers. The movement of 100% outside air through the system can require more fan energy than the baseline case, as the economizer design requires more ducting, which increases air resistance through the system. However, during this 100% outside air mode the cooling is provided without operating the chiller, chilled water pumps, condenser water pumps, or the cooling tower fans. Outside air is also provided instead of recirculated air whenever the outside air temperature is greater than the supply air temperature but lower than that of the return air. Under this condition the chiller must operate, but the cooling required of the chiller is less than in a case with complete recirculation.

Energy modeling protocol

For each design scenario, the model calculations assume a 30,000 ft^2 (2800 m^2) data center with an internal heat density of approximately 80 W/ft^2 (0.86 kW/m^2; 2.4 MW total) This size and power density are characteristic of data centers evaluated in previous studies (Shehabi et al. 2008; Greenberg et al. 2006; Tschudi et al. 2003). The size of data centers varies greatly; 30,000 ft^2 is within the largest industry size classification, which is responsible for most servers in the US (IDC 2007). Power density in data centers is rapidly increasing (Uptime Institute 2000) and a power density of 80 W/ft^2 is currently considered to be of low- to mid-range (Rumsey 2008).

Basic properties of the modeled data center for all three scenarios are summarized in Table 1. Energy demand is calculated as the sum of the loads generated by servers, chiller use, fan operation, transformer and uninterruptible power supply (UPS) losses, and building lighting. The chiller encompasses coolant compressor, chilled water pumps, condensing water pumps, humidification pumps, and cooling-tower fans. Energy demand for servers, UPS, and lighting are constant, unaffected by the different design scenarios, but are included to determine total building-energy use. The base case and WSE scenarios assume conventional humidity restrictions recommend by ASHRAE (ASHRAE 2005). The ASE scenario assumes no humidity restriction, which is an adjustment required to gain ASE benefits as is typical in ASE implementation (Rumsey 2008). Air-side economizers also require a different air distribution design and the fan parameters associated with each design scenario are listed in Table 2. The properties of other pumps and fans throughout the HVAC system remain constant for all three scenarios. Values are from previous data-center energy analyses (Rumsey 2008; Rumsey 2005).

The energy modeling approach used in this study applies a previously used protocol (Rumsey 2008; Rumsery 2005) and is based on a combination of fundamental HVAC sizing equations that apply equipment size and efficiencies observed through professional experience. Building energy modeling is typically performed using energy models such as DOE-2, which simultaneously models heat sources and losses within the building and through the building envelope. However, models such as DOE-2 are not designed to incorporate some of the HVAC characteristics unique to data centers. Also, data centers have floor-area-weighted power densities that are 15-100 times higher than those of typical commercial buildings (Greenberg et al. 2006). This allows accurate modeling of data-center energy use to focus exclusively on internal heat load and the thermal properties of outdoor air entering the building. This is the approach taken in this study, as heat generated from data center occupants and heat transfer through the building envelope are negligible relative to the heat produced by servers. The building envelope may influence the cooling load in low-density data centers housed in older buildings that have minimal insulation. Evaluating this building type is worthy of exploration, but the required analysis is more complex and outside the scope of the present paper.

Both air-side and water-side economizers are designed to allow the chiller to shut down or reduce chiller energy load under appropriate weather conditions. Less overall energy is required for operation when the chiller load is reduced, but chiller efficiency is compromised. Changes in chiller efficiency used in this analysis are shown in Figure 2, representing a water-cooled centrifugal chiller with a capacity > 300 tons and condenser water temperature of 80 °F. A chilled water temperature of 45 °F, which is standard practice for data center operation, is used in the base case and ASE scenario. The WSE scenario uses a chilled water temperature of 52 °F, which is common when using water-side economizers. This increases needed airflow rates but allows greater use of the water-side economizers. The curves are based on the DOE2.1E software model and apply coefficients specified in the Nonresidential Alternative Calculation Method (ACM) Approval Manual for the 2005 Building Energy Efficiency Standards for Residential and Nonresidential Buildings (CEC 2005).

Annual data center energy use is evaluated for each of the three configuration scenarios assuming that a data center building is located in each of the five cities shown in Figure 3. Weather conditions at each city are based on hourly DOE2.1E weather data for California climate zones (CEC 2005).

Results and Discussion

Results from each scenario modeled are presented in Table 3 as a “performance ratio” which equals the ratio of total building energy divided by the energy required to operate the computer servers. Lower value of the performance ratio implies better energy utilization of the

HVAC system. The performance ratio for the base case is 1.55 and, as expected, is the same for all the cities analyzed, since the operation of this design is practically independent of outdoor weather conditions. The base case performance ratio is better than the current stock of data centers in the US (EPA 2007; Koomey 2007) because the base case represents newer data centers with water-cooled chillers, which are more efficient than the air-cooled chillers and direct expansion (DX) cooling systems found in older data centers.

The performance ratios for the ASE and WSE scenarios show air-side economizers consistently provide savings relative to the base case, though the difference in savings between the two scenarios varies. It is important the note that even small changes in the performance ratio results in significant savings, given the large amount of energy used in data centers. For example, reducing the performance ratio at the model data center in San Jose from 1.55 to 1.44 represents a savings of about 1.9 million kWh/y, which corresponds to a cost savings of more than $130,000/y (assuming $0.07/kWh).

Figure 4 shows the disaggregation of the cooling systems' annual energy use, normalized by floor area, for each modeled data center by location and design scenario. The annual energy use dedicated to the servers, USP, and lighting is 584, 95, and 9 kWh/ft^2, respectively. These energy values are independent of the climate and HVAC design in scenario and not included in the graphs in Figure 4. Economizer use is typically controlled by combination of outside air temperature, humidity, and enthalpy; however results shown in Figure 4 are for economizer use controlled by outside air temperature only. Results show that the ASE scenario provides the greatest savings in San Francisco while Fresno provides the least ASE savings. Sacramento benefited the most from the WSE scenario while minimal savings were realized in Los Angeles and San Francisco. The San Francisco WSE scenario, where significant gains would be expected because of the cool climate, is hindered by chiller part-load inefficiencies. The relatively higher moisture content in the San Francisco air increases the latent cooling load in the model and causes the chiller plant to reach the capacity limit of the first chiller more often, activating a second chiller. The second chiller shares the cooling load equally with the first, resulting in a transition from one chiller at a high load factor (efficient operation) to two chillers at slightly above half the load factor (less efficient operation). The results from the WSE scenario in San Francisco emphasize the need for engineers to model the hour-by-hour load, rather than just the peak load, and to size chillers such that all active chillers at any moment will be running near their most efficient operating point.

Figure 5 shows that removing the humidity restrictions commonly applied to data centers is necessary to gain ASE energy savings. As the relative humidity (RH) ranged is narrowed, energy use from the fans begins to sharply increase, surpassing the equivalent baseline energy in most of the cities. Humidity levels are often restricted in data centers to minimize potential server reliability issues. ASHRAE's guidelines released in 2005 for data centers provide a "recommend" RH range between 40-55% and an "allowable" range between 20-80% (ASHRAE 2005). There is minimal cost in applying the more conservative ASHRAE RH restrictions in conventional data center design, such as the baseline in this study shown in Figure 5. The influence of humidity on server performance, however, is poorly documented and the need for humidity restrictions is increasingly being questioned (Fontecchio 2007). The energy saving difference between adhering to ASHRAE's recommend RH range versus the allowable RH range is substantial, and warrants further investigation.

Conclusion

Employing the energy-saving measures evaluated in this paper would require a shift in conventional data center design and operation. Various operational concerns must be addressed before widespread adoption of these technologies could be expected in data-center buildings. This paper contributes to the informed implementation of air-side and water-side economizers by assessing the energy benefits of adopting these efficiency improvements. Air-side economizers are shown to consistently outperform water-side economizers in California, though the difference in performance varies by the climate conditions of the locations evaluated. Furthermore, the models show that conventional humidity restrictions must by relaxed or removed to substantially realize the energy benefits of air-side economizers. As the data center economy continues to rapidly grow, energy efficiency will continue to emerge as an important financial and environmental concern. The results presented here contribute to our understanding of different design implications and should assist decision makers in the implementation of energy-efficient data centers.

Acknowledgments

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Table 1: Data Center Characteristics Common to All Design Scenarios

Data Center Parameters	
Floor Area	30,000 ft^2
UPS Waste Heat	326 kW
Data Center Lights	30 kW
Total Rack Load	2000 kW
Total Internal Load	2,356 kW
Average Internal Load Density	79 W/ft^2
Minimum Ventilation	4,500 ft^3/min
Supply Air Temperature	55 ¡F
Return Air Drybulb Setpoint	72 ¡F
Chiller Capacity	1750 kW
Number of Chillers	3

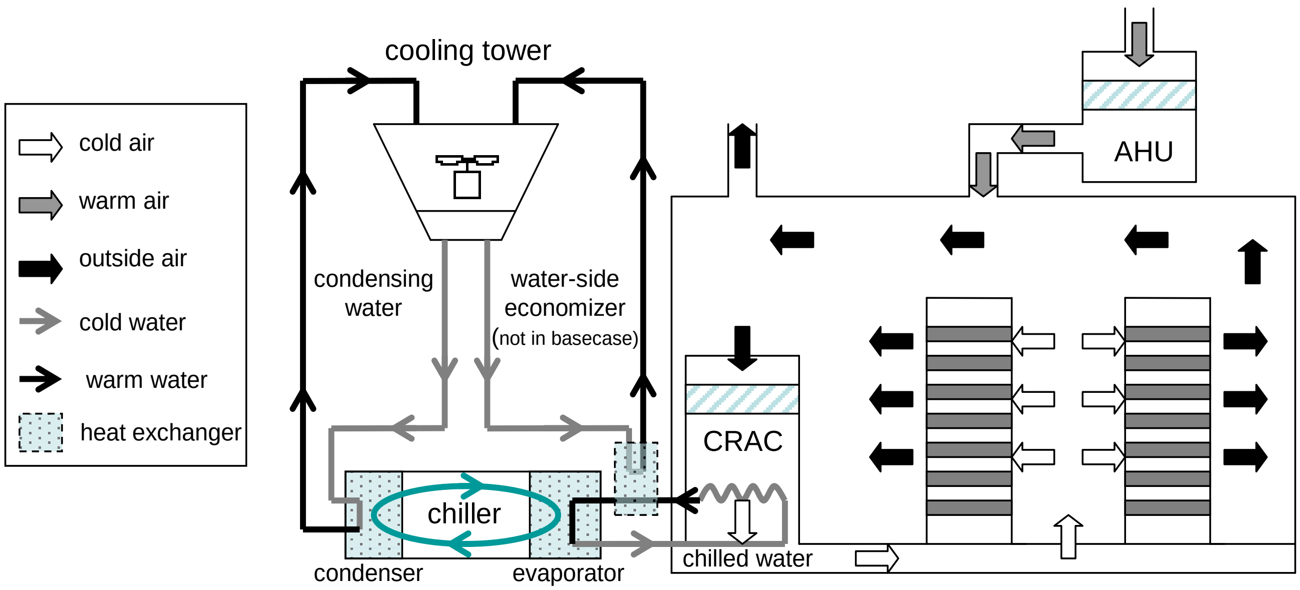
Table 2: Data Center Fan Properties

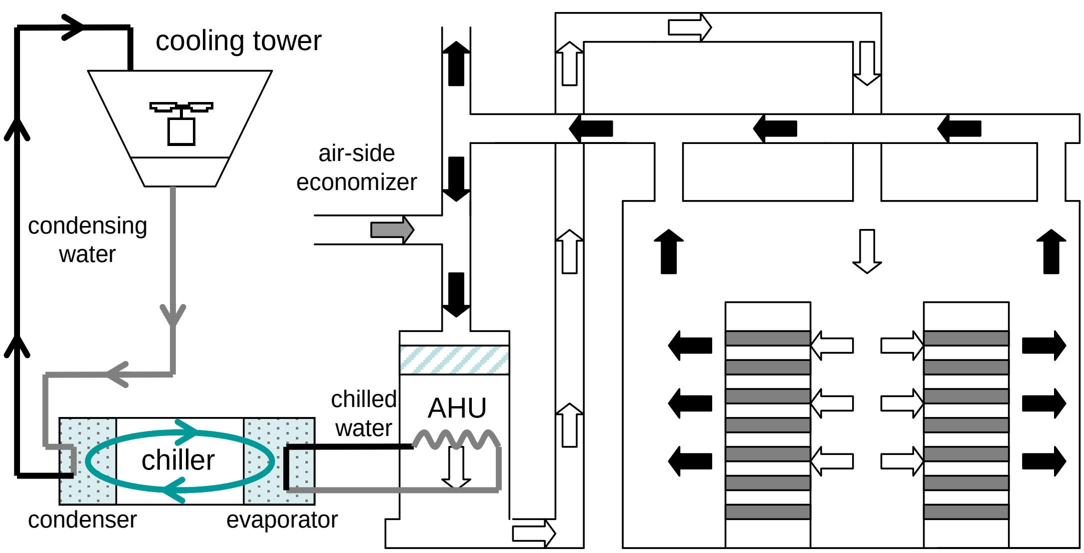
Fan System Parameters	**Baseline and WSE**			**ASE**	
	MUAH	Exhaust	CRACs	Supply	Relief
Total Air Flow (cfm)	4,500	4,500	495,000	437,758	437,758
Fan Motor Size, Nominal (hp)	7.5	3	10	30	50
Number of Fans	1	1	30	10	5
Fan Efficiency	53.3%	44.0%	55.6%	63.8%	67.5%
Fan Drive Efficiency	95%	95%	95%	95%	95%
Fan Motor Efficiency	89.6%	86.2%	90.1%	92.5%	93.2%
VFD Efficiency	n/a	n/a	n/a	98%	98%
Total Static Pressure Drop (in w.g.)	3.5	1	1.6	2	1

Table 3: Ratio of Total Building Energy to Computer Server Energy

	San Jose	**San Francisco**	**Sacramento**	**Fresno**	**Los Angeles**
Baseline	1.55	1.55	1.55	1.55	1.55
Air-side Economizer	1.44	1.42	1.44	1.46	1.46
Water-side Economizer	1.53	1.54	1.53	1.53	1.54

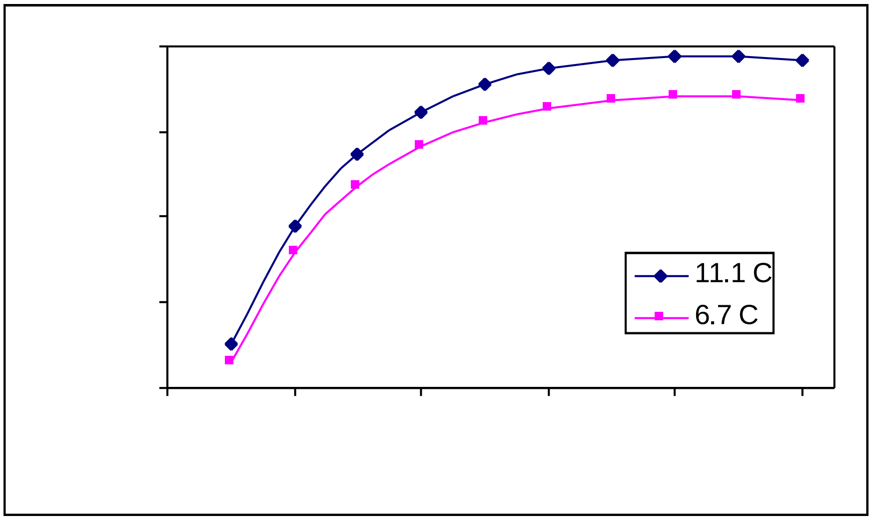
Figure 1: Schematic of Data Center Cooling Design Scenarios





Air and water flow schematic for the basecase and water-side economizer scenarios (above).
Air and water flow schematic for the air-side economizer scenario (below).

Figure 2: Assumed Part Load Performance of Data Center Chillers



Part load efficiencies for a water-cooled centrifugal chiller with a capacity >300 tons and an condenser water temperature of 26.7 °C (CEC, 2005))

Figure 3: Evaluated Climate Zone Locations

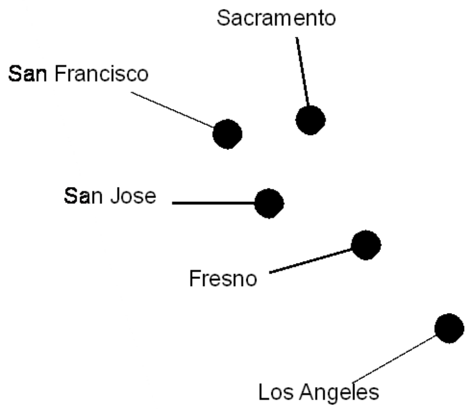


Figure 4: Disaggregated Energy Use (Climate Dependent Values Only)

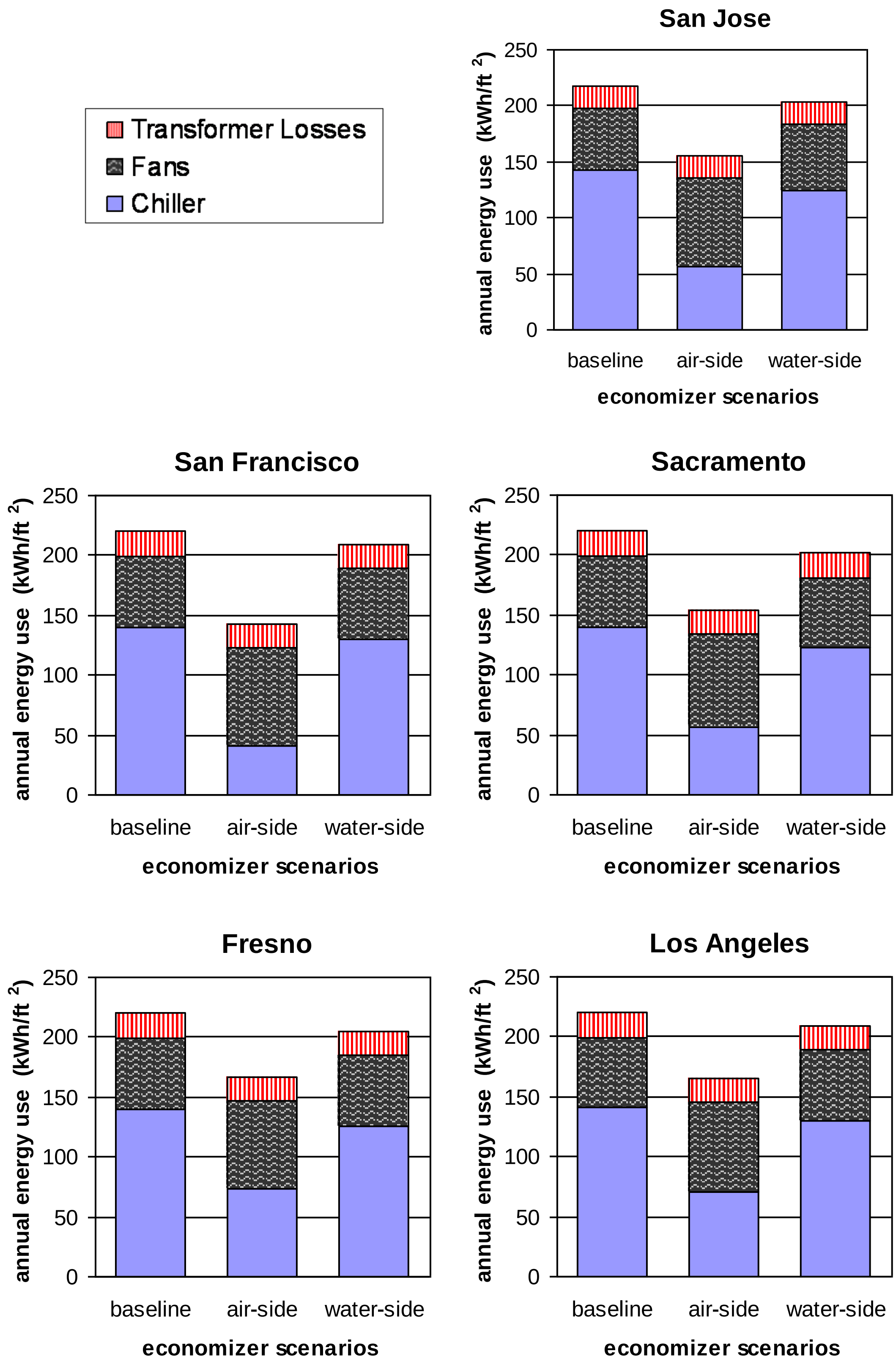
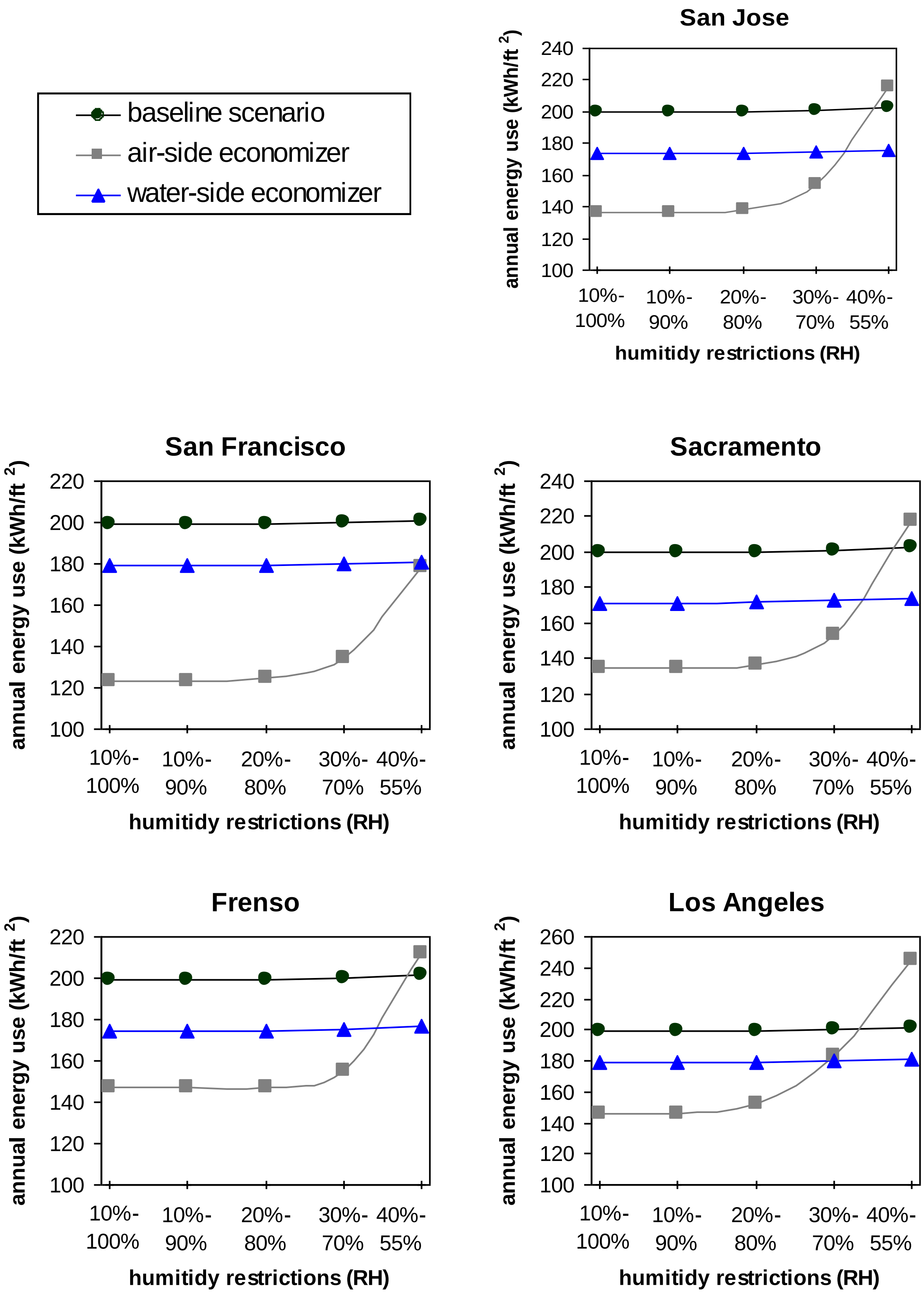


Figure 5: Chiller and Fan Energy Resulting from Humidity Restrictions



Appendix C

Climate-Dependent Data Center Modeling

Refer to pdf version of the report for the data center modeling files.